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A Review on IoT-Driven Digital Ecosystems for Intelligent and Sustainable Systems

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***Abstract*— The evolution of the Internet of Things (IoT) has enabled traditional embedded systems to become intelligent and connected systems that can sense, compute, and communicate through communication networks. Through the incorporation of sensors, actuators, microcontrollers, and Internet connectivity, the IoT-enabled embedded systems have been able to provide monitoring capabilities, control functionalities, and computing functionalities for real-time information processing.**

The rising demand for faster communication, improved security measures, energy efficiency, smaller hardware sizes, and improved connectivity has contributed to the adoption of IoT in engineering applications.

The current paper explores the concepts of IoT-based monitoring and control systems in terms of their architectures, communication technologies, sensing technologies, and implementation technologies.

The current paper also explores the increased usage of these systems in various applications such as industrial automation, healthcare, consumer electronics, automotive systems, smart home systems, telemedicine, and smart cities.

***Keywords*— Internet of Things (IoT), Embedded Systems, Smart Devices, Remote Monitoring, Industrial IoT, Sensors, Automation, Smart Cities.**

I. INTRODUCTION

The development of the digital technologies has been fast, making it possible to integrate the embedded systems with the internet connectivity and hence, the use of Internet of Things (IoT) in various applications has become prevalent. While the terms embedded system and IoT embedded system are interchangeably used, they mean different things.

Embedded systems are computing systems that are tailored to perform certain tasks using the least energy and real time with reliable operations. IoT embedded systems, on the other hand, add functionality to traditional embedded systems through the provision of interfaces for communication and internet connectivity and hence making it easier to interact with other smart systems, cloud services and edge computing facilities. The enhanced connectivity enables IoT embedded systems to perform data collection in real time, remote monitoring, intelligent control, predictive analysis and decision making. Therefore, IoT embedded systems are necessary for applications such as industrial automation, healthcare, smart cities, transport, agriculture and consumer electronics [1]–[3].

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A. What is IoT?

The Internet of Things (IoT) represents an infrastructure comprised of physical objects that have been integrated with various sensors, processors, software applications, and networking capability to connect and communicate with each other on the internet with little or no human involvement. Through enabling efficient communication between devices, IoT facilitates intelligent automation, real-time monitoring, and decision-making based on data. With the rise of smart devices like health monitors, connected home appliances, intelligent transportations, and industrial machines, the IoT landscape has gained more relevance in daily activities. A good example would be an intelligent refrigerator that is able to keep track of the stored food items along with their expiry date and notify the user when a re-stock is required. According to ITU, there are four major dimensions of IoT as depicted in Figure 1. This includes the identification of physical objects through means such as RFID and barcodes, data sensing and processing, embedding devices within miniature sizes, and intelligent systems that operate independently [1]-[4].

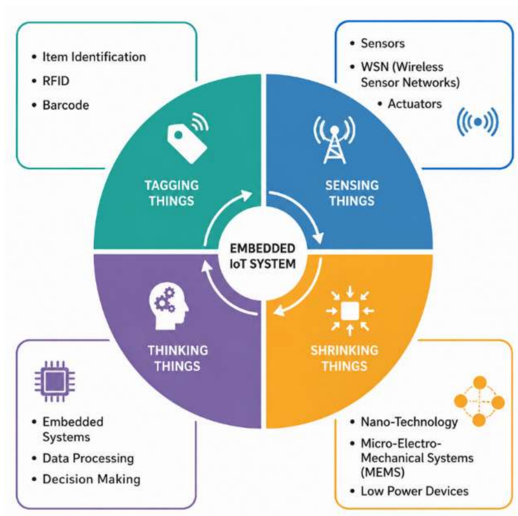

Figure.1 Four dimensions of IoT by ITU

B. What is an Embedded System?

Embedded System refers to the computer-based system that can be used in a larger system to carry out some specific function. An embedded system is used to accomplish a certain function, and hence it is not a general purpose computer but one designed to carry out specific functions. The main features of an embedded system are reliability, real-time operation, low power consumption, and compact design. These systems typically comprise a microcontroller or microprocessor, memory, input/output interface, and software that can perform some function. Modern days embedded systems use sensors and actuators, which help in acquiring, processing and controlling environmental data in real time. The communication technology has helped in the development of the embedded system into intelligent connected devices forming the backbone of the Internet of things (IoT) applications [1]–[4].

II. Distinction Between Embedded Systems and IoT Embedded Systems

While there are similarities between embedded systems and IoT embedded systems in terms of hardware elements, there are differences regarding their functions and communication abilities. Traditional embedded system has the ability to carry out specific functions without being connected to the Internet. However, an IoT embedded system is characterized by the inclusion of communication capabilities, which ensure constant communication with other devices on the cloud and on the network through networking protocols. These features make IoT embedded systems more advanced than traditional embedded systems [1]-[3].

Embedded systems represent the basic hardware platforms on which IoT applications run. They comprise a combination of processors, memory, sensors, actuators, and application-specific software to perform certain tasks. IoT extends the functionality of embedded systems by making their communication possible to create smart ecosystems for distributed sensing, collaborative computing, and autonomous control. Thus, embedded systems should be treated as indispensable tools for implementation of the Internet of Things rather than as an alternative to it [1], [2].

The second difference is related to the software platform. Ordinary embedded systems typically run lightweight firmware or RTOS to ensure deterministic timing constraints. IoT embedded systems can use firmware or RTOS as well; nevertheless, powerful devices more frequently use embedded operating systems like Embedded Linux or Android Things to implement networking, security, integration with cloud infrastructure, and over-the-air updates of software. The selection of the software platform depends not only on Internet connectivity but also on the complexity of the application and other factors [2], [4].

The embedded systems provide the basic hardware infrastructure for the development of IoT applications. Embedded systems include processor, memory, sensors, actuators, and application software to perform the task. The expansion in the abilities of IoT is done by making connections between several embedded systems to form an intelligent network to do collaborative sensing, data processing, and autonomous control. Embedded systems can be considered as an important element of IoT applications and not as an alternative to it [1], [2].

With the advent of edge computing, artificial intelligence, TinyML, blockchain, and 5G/6G communication technology, IoT embedded systems have become intelligent cyber-physical systems that have predictive analytics capabilities and secure distributed computation capabilities. This has led to a considerable increase in IoT applications in industrial automation, healthcare, transport, agriculture, smart home, and smart city infrastructures [1], [3], [5].

III. Types of IoT Embedded Systems

Classification of IoT embedded systems is possible based on their hardware, software, and application needs. All IoT embedded devices use the concept of embedded software that can vary from simple firmware to complex embedded operating systems with networking, multitasking, and cloud computing capabilities. The software layer allows for a smooth interaction between sensors, actuators, communications, and other components with IoT platforms [2], [4].

Embedded device is a hardware device that has been created to achieve one or several specific functionalities by making use of efficient and economical usage of resources. Embedded devices typically consist of microcontrollers, communication ports, sensors, and software for performing certain actions within an overall Internet-of-Things environment.

In order to classify IoT embedded systems based on the amount of computations performed, these systems can be classified into microcontroller systems, microprocessor systems, edge AI devices, and industrial embedded controllers [1], [3].

Some of the representative examples are POS terminals, self-service kiosks, health trackers, smart meters, controllers, connected cars, environmental monitoring systems, smart agriculture sensors, and smart home appliances. The combination of all these sensors provides functionalities such as real-time sensing, remote diagnostics, predictive maintenance, and automated control for various domains including manufacturing, healthcare, transportation, retail, agriculture, and smart city infrastructures. This demonstrates the increasing relevance of IoT-enabled embedded systems in today’s digital environment [1], [4], [5].

IV. IoT Embedded system in Automotive Industry:

However, there have been changes within the automobile industry as a result of embedding the Internet of Things (IoT), thus resulting in the automation of vehicles. Today’s automobiles are equipped with many embedded sensors, electronic control units (ECUs), wireless communication devices, and cloud computing platforms to provide continuous monitoring of the vehicle status, driver's behavior, and the environment. These help in conducting real-time diagnosis, preventive maintenance, smart navigation, remote monitoring, and road safety [6]–[9].

A. Internal Combustion Engines

Embedded systems powered by the IoT constantly measure important factors like engine temperature, RPM, fuel consumption, oil pressure, coolant temperature, battery voltage, and tire pressure. Constant monitoring helps detect any anomalies in the performance of the engine, thus increasing engine reliability, saving on maintenance cost, and avoiding any vehicle failures [7], [8]. If the engine becomes overheated, the process of combustion will become less efficient, thus leading to increased fuel consumption and faster wear of the engine parts, along with higher greenhouse gas emissions [7], [9].

Figure.2: Urban Social Internet of Vehicles System

When AI is integrated with IoT, it provides enhanced engine diagnostics through predictive maintenance and intelligent fault detection. Some of the sensors employed in this include cameras, radar, LiDAR, GPS, and IMUs to help with obstacle detection, lane detection, road condition assessment, and adaptive navigation. These technologies greatly enhance vehicle safety, efficiency, and driving experience [9], [10]. Communication between vehicles, road side facilities, cloud-based servers, and traffic management centers is achieved by using technologies called Internet of Vehicles (IoV) or Social Internet of Vehicles (SIoV). Communication techniques such as Vehicle to Vehicle (V2V), Vehicle to Infrastructure (V2I), and Vehicle to Everything (V2X) provide solutions for avoiding collisions, cooperative driving, route planning, traffic control, and emergency situations. Figure 2 shows a typical city SIoV system architecture [9]–[11].

B. Battery Management Systems:

The Battery Management System (BMS) is an important part of any electric vehicle (EV), hybrid electric vehicle (HEV), and renewable energy storage system. The IoT-based BMS collects data regarding battery voltage, current, temperature, number of charging and discharging cycles, etc., ensuring the safety and efficient operation of batteries. The information is gathered through sensors embedded within the battery and processed locally before being uploaded to cloud platforms [8], [10].

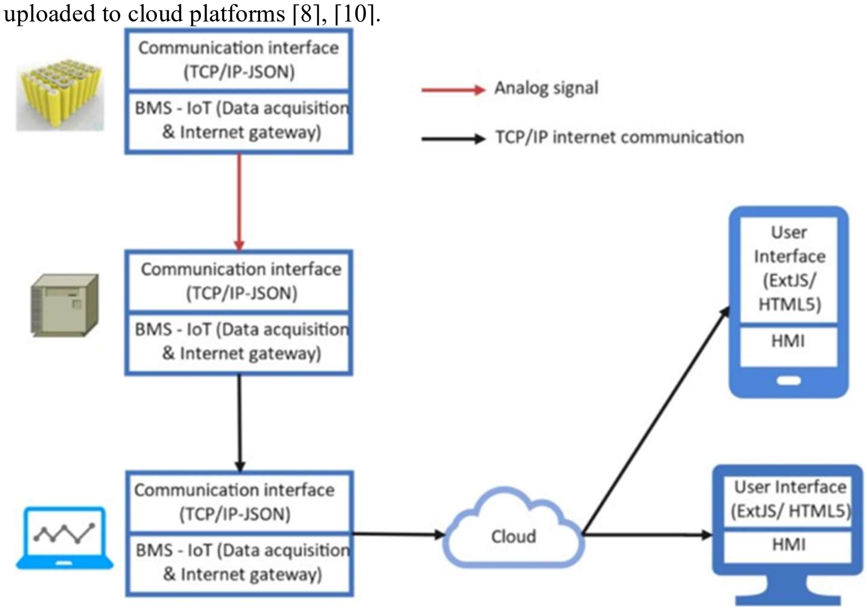

Figure.3: IoT based BMS

Furthermore, machine learning and data analytics can help increase battery efficiency through proper estimation of the State of Charge (SOC), State of Health (SOH), and Remaining Useful Life (RUL). Such forecasting abilities will ensure that batteries are charged optimally, will have a long life span, will be energy efficient, and maintenance costs will be reduced. Detecting abnormal thermal characteristics of the battery at an early stage will prevent its degradation and avoid thermal runaway [8], [10].

Cloud computing offers assistance to IoT-assisted battery management in terms of scalable storage, remote access, centralized monitoring, and analytics. It helps manufacturers and fleet managers to monitor the behavior of batteries, analyze operating data, perform predictive maintenance, and optimize fleet operations. Other than automotive applications, the IoT-assisted BMS has been deployed in other sectors like smart grid, photovoltaics, renewable energy integration, and microgrid infrastructure. Figure 3 shows a typical IoT-assisted Battery Management System deployed within the smart microgrid environment [6], [8], [10], [11].

C. Fuel Cells

Fuel cells have come out as an innovative alternative to traditional batteries that power EVs, providing a sustainable option to decrease carbon footprints in the transport industry. FCVs derive their energy from the process of electrochemical reaction between hydrogen and oxygen, resulting in the emission of water vapor as a sole by-product. In comparison to BEVs, FCVs have a number of operational benefits, which include fast refueling, extended driving range, and limited reliance on charging facilities [12], [13].

The incorporation of IoT technologies has greatly improved the performance and stability of fuel cell systems due to the constant monitoring of important parameters such as the temperature of the stack, hydrogen pressure, humidity, airflow, voltage distribution, and output power. With sensors embedded into the system along with cloud computing and edge intelligence, real-time monitoring, predictive maintenance, diagnostics, and optimization of energy consumption can be achieved. Machine learning can help detect anomalies like flooding of cells, degradation of membranes, leakage of gases, and imbalance in stacks before any failure occurs [13]–[15].

FCEVs that use IoT also have advanced intelligent transportation technologies which include V2X communication, cloud-based navigation, fleet management, and assistance in autonomous driving. Communication between the vehicle, infrastructure, and traffic control system allows for dynamic route planning, location of hydrogen stations, navigation, and intelligent energy usage [9], [10], [16].

Even with all these benefits, the deployment of FCVs is hindered by the lack of hydrogen production plants and filling stations, as well as the high cost of hydrogen production and storage. The future research will be directed at incorporating IoT, artificial intelligence, digital twin, and edge computing in hydrogen infrastructure management and fuel utilization for the development of autonomous hydrogen fuelled transport. With the further development of these technologies, the commercialization of FCEVs will become a reality [11]-[16].

V. IoT Embedded system in Healthcare:

Digital transformation has taken place in the field of healthcare through the deployment of embedded IoT systems, resulting in the emergence of Internet of Medical Things (IoMT). These intelligent devices use embedded sensors, wearable devices, communication technology, cloud computing, and artificial intelligence (AI) to provide remote monitoring of patients, remote diagnosis, and personalized healthcare solutions. The IoT-based healthcare system helps to collect real-time physiological data, thus helping to make remote monitoring of patients possible and improving clinical decisions. The integration of embedded intelligence and wireless communication has greatly improved healthcare accessibility, especially for old age people, chronic patients, and people living in distant locations [17]–[20].

A. IoT based Healthcare Security Systems

The integration of connected medical devices has posed serious issues concerning cybersecurity and privacy in today's healthcare environment. Connected medical devices including wearable sensors, infusion pumps, pacemakers, imaging machines, and remote monitoring systems constantly transfer confidential patient data over the communication network and thus pose potential security risks in terms of unauthorized access, data manipulation, ransomware attack, and denial of service. Confidentiality, integrity, authentication, and security of communication have therefore become a basic requirement in healthcare networks using the Internet of Things (IoT) technology [17], [21], [22].

Advances in blockchain technology have offered decentralized approaches for the security of healthcare data through an unchangeable transaction log, encryption, and distributed access control. However, traditional blockchain approaches have high computation cost, storage cost, and energy cost, making them unsuitable for IoT devices with limited resources. Decentralized approaches like Holochain and SDN-based blockchain approach have been introduced to counter these challenges through the reduction of computational cost, reduced network traffic, and scalability, while maintaining the secure transfer of data. These technologies help in the secure exchange of EHRs, identity management, and reliable communications between hospitals, doctors, patients, and medical IoT devices [21]–[24]. Figure 4 shows an example of a secure healthcare architecture using blockchain and Holochain technologies for the security of medical data in IoMT environments.

The recent studies have considered designing lightweight blockchain architectures that address the computational constraints of traditional blockchain within constrained IoT settings. The use of SDN combined with blockchain is an interesting concept where programmable SDN controllers manage network resources, access control, and routing policy in addition to secure data sharing. Compared with traditional blockchain, this structure provides network flexibility, better privacy protection, and low computational complexity, memory usage, and communication latency [23], [24].

Another innovative distributed ledger technology is Holochain that has recently received some attention as a viable security system for IoT healthcare systems. While traditional blockchain requires global consensus, thus increasing storage, network traffic, and energy consumption, Holochain uses an agent-based structure that makes it possible to get rid of global consensus, thus decreasing storage, network traffic, and energy consumption. Holochain becomes quite applicable for embedded IoT devices with low computational power and limited memory resources due to its lightweight nature, which allows for enhanced scalability, transaction validation, low communication overhead, and high speed. Figure 4 depicts the concept of a blockchain and Holochain-based security framework for IoT healthcare systems [22] – [24].

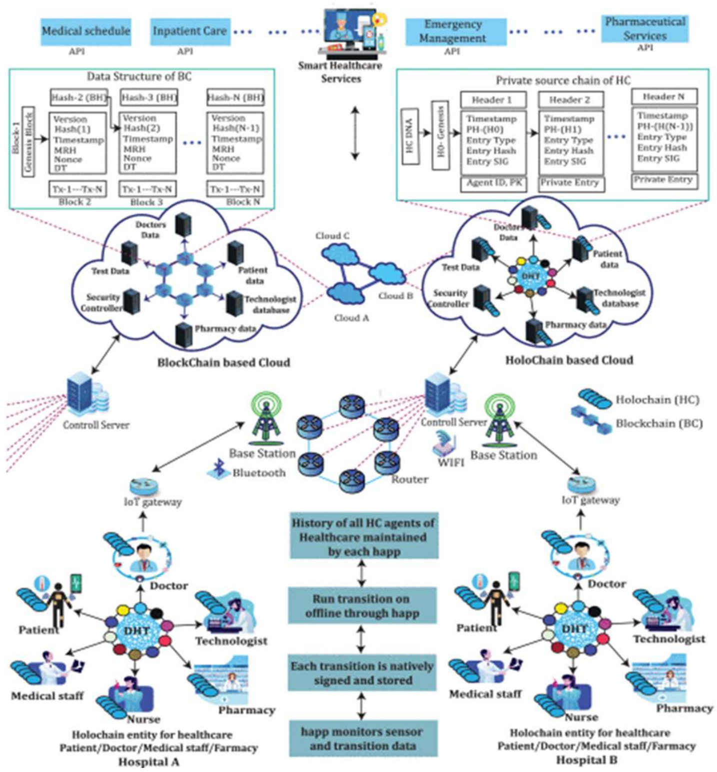

Figure.4 Block chain and holochain security network system

B. Embedded AI-Based Digi-Healthcare

The combination of IoMT, AI, and edge computing has made it possible to design smart digital healthcare solutions that can continuously monitor patients and assist in clinical decision making. In these solutions, physiological parameters such as heart rate, blood oxygen saturation (SpO_2), body temperature, blood pressure, and ECG signals are sensed using medical and wearable sensors. These sensed data are communicated through wireless communication protocols to an edge computing device for data processing, feature extraction, and inference using machine learning algorithms to detect any abnormalities in a patient's health condition [18], [25]. Edge intelligence greatly enhances the responsiveness of health care by enabling notifications to be instantly raised when any kind of irregular physiological behavior is detected. Automatic notifications may be sent to patients, caregivers, and health care practitioners for timely interventions, while minimizing reliance on uninterrupted cloud connection. On the other hand, processed data and the outcomes of the predictive models may be securely stored in cloud servers. Figure 5 shows the architecture of a health care system using the IoMT and AI technologies [18], [25].

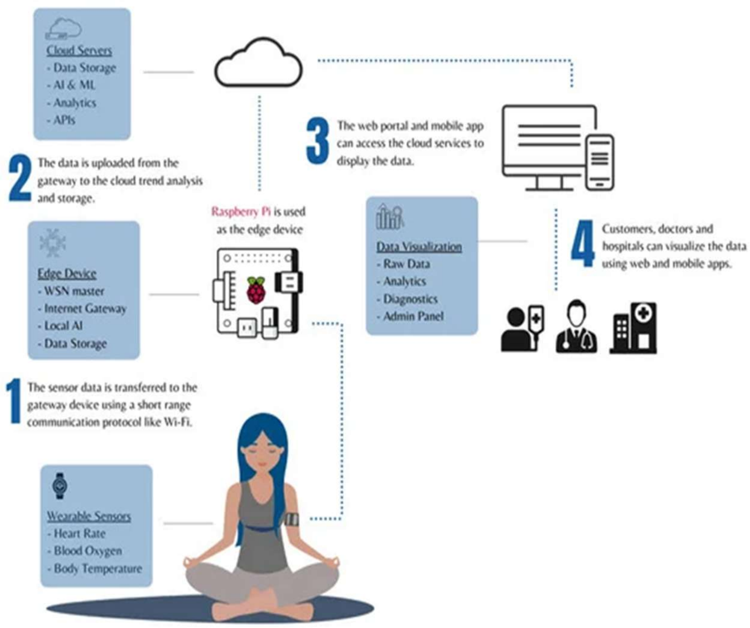

Figure.5: Architecture diagram of the IoMT & AI based system.

The edge node will pre-process the collected physiological data prior to sending it to the cloud infrastructure where computationally intensive computations are carried out via the use of high performance computing capabilities [18], [25]. Once training has been completed, the optimized model is sent back to the edge node through cloud service providers like AWS to analyze the live data from the sensors [25]. The integration of edge and cloud platforms will greatly enhance efficiency and quicken the detection of abnormalities in the physiological signals. The output obtained from the analysis along with the processed sensor data and past health records can be synchronized with a web-based portal where authorized users, which include physicians, caregivers, and the patient himself, can view the data and make clinical decisions based on artificial intelligence [18], [25].

The IoMT-powered healthcare solution comprises of sensing technologies, edge computing, cloud computing, and artificial intelligence that will be used for continuous health monitoring and clinical decision making. Implementation of the solution involves two key elements: hardware development and software development.

Hardware development (IoT node design, edge device)

Hardware platform uses the IoT node with ESP32 microcontroller, which ensures in-built Wi-Fi connection to enable the interaction between the wearable sensors and the edge device [18], [26]. Heart rate, SpO2, and body temperature measurements are done using medical-grade sensors like the MAX30102 pulse oximeter sensor and the MLX90614 infrared temperature sensor. The measured data is then sent to the edge device where the data is processed, filtered, and aggregated for analysis. Data processing at the edge level ensures that there are minimal delays when communicating with the health monitoring systems [18], [19].

Software development (health state prediction module)

The software framework uses a structured approach consisting of data collection, preprocessing, feature extraction, machine learning model training, evaluation, and deployment, as shown in Figure 6.

Figure.6: The development process for the health status prediction module.

Physiological data obtained through wearable sensors undergo pre-processing, normalization, and conversion into significant features in order to enhance the accuracy of prediction. Heavy computation involving the training of machine learning models takes place in the cloud computing system, which offers scalable computing power and storage [18], [25]. After training and optimizing the best model, it will be deployed in the edge computing device via cloud systems such as Amazon Web Services (AWS). Edge-cloud computing system ensures low latency while also being capable of rapidly detecting any abnormal physiological state. The sensor data, predictions, and patient history are synced into a web-based interface where authorized individuals, including doctors, caregivers, and patients can access the health data in real time [18], [25].

The developed prototype of the IoMT reveals the possibilities of the combination of the embedded systems, AI, and cloud computing in intelligent applications in healthcare. The ability to constantly monitor the vital parameters helps to detect any abnormalities in health status and provide timely medical intervention, thus increasing patient outcome. Remote monitoring of patients based on IoT technologies provides increased accessibility, constant monitoring, and better healthcare services delivery in comparison to traditional healthcare based in hospitals, especially in rural areas. Moreover, the proposed system can be enhanced using other biomedical sensors, such as ECG, blood pressure, breathing rate, glucose, and other sensors [18], [19], [25].

IoT-Based Smart Health Monitoring System for COVID-19

The outbreak of the COVID-19 virus has fast-tracked the implementation of IoT-based remote healthcare services to minimize the physical contact between the patient and healthcare service provider without compromising the medical supervision of the individual. The IoT based healthcare monitoring system allows the patients to stay quarantined at home, and their physiological metrics are monitored continuously by the healthcare service provider. This IoT system measures the vital signs of a person, including body temperature, heart rate, blood pressure, blood oxygen levels (SpO_2), and the breathing pattern. This remote healthcare solution can be quite helpful in remote areas that lack specialized healthcare facilities [19], [27].

In the IoT healthcare system, the use of wearable biomedical sensors, embedded controllers, wireless technology, cloud computing, and web-based user interface facilitates the real-time surveillance of patients. Physiological data collected through sensors are digitized by embedded microcontrollers prior to sending the data to an edge device or Raspberry Pi for pre-processing and analysis. The preprocessed data is then uploaded to cloud platforms like ThingSpeak, where the data is safely stored for real-time monitoring and analysis. Figure 7 shows the structure of a conventional IoT-based healthcare system.

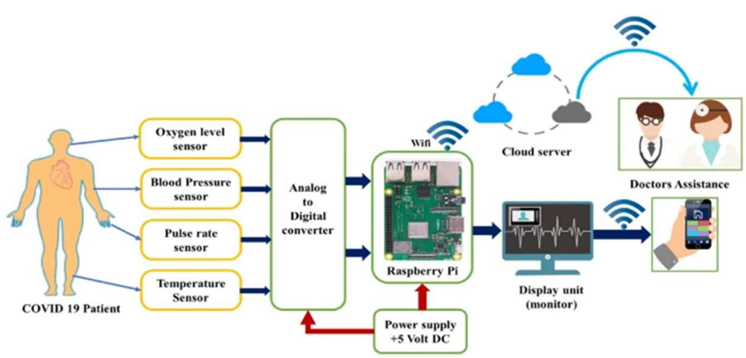

Figure.7: Block diagram of the IOT smart health system

Architecture of the system involves three main phases: data acquisition, data processing, and visualization of results. In the phase of data acquisition, wearable sensors are used for the constant measurement of physiological signals and their subsequent transmission to an embedded controller through proper communication channels.

The embedded controller processes the data by performing the process of signal conditioning, analogue to digital conversion, and preliminary processing before sending the data to cloud computing services. Physicians can access the data on a web portal on a real-time basis [18], [19], [25].
IoT-powered monitoring systems provide constant monitoring of patients, fast alerts for emergencies, less time spent in hospitals, and increased access to healthcare services when compared to traditional hospital-based healthcare facilities. The use of artificial intelligence will further enhance IoT-based healthcare systems, allowing for automatic detection of anomalies, health risks, and clinical suggestions. In future IoT-powered healthcare systems, more biomedical sensors are anticipated to be integrated into them along with edge intelligence and federated learning, such as electrocardiogram (ECG), breathing rate, glucose level monitoring, and blood pressure sensors [18], [19], [24], [27].

VI. IoT Embedded System in Education:

A remarkable shift to digital education has been observed by the education industry in the wake of the COVID-19 outbreak, which has expedited the use of Internet of Things (IoT) based embedded systems in smart educational environments. The use of embedded devices along with wireless communication, cloud computing, and artificial intelligence has provided educational organizations the ability to provide interactive, adaptive, and personalized learning in an environment other than the traditional classroom [28], [29].

A. Embedded IoT based Interaction system

IoT-based interaction systems are aimed at creation of immersive and collaborative learning environment through connection of physical educational resources with their digital twins. IoT-based interaction systems use embedded devices along with the Internet of Things technologies that enable students to interact with laboratory equipment, teaching material, and educational objects via smartphones, tablets, or any other type of smart device. Technologies like Near Field Communication (NFC) and Quick Response (QR) code are widely used for unique identification of learning resources and creating links to the multimedia content such as videos, animations, simulations, digital documents, and interactive web applications [28].
In a standard IoT-enabled learning environment, each learning object has its unique digital identity that includes contextual data as well as smooth interaction between learners and learning objects. Mobile apps that have NFC and QR codes read capabilities fetch learning material immediately, while wireless connectivity via Wi-Fi or cell networks allows learners to connect to cloud-based education platforms. In order to provide fast interaction, lightweight communication protocol, for example, WebSocket, is used, which facilitates synchronization between client device and education servers. An architectural diagram of a sample IoT-enabled interaction system for smart education is provided in Figure 8 [28], [29].
Management of the server infrastructure falls within the hands of the instructor or educational institution, and learning resources, assessments, and activity logs of students are stored there. The student's mobile application accesses the server for retrieving digital learning material, submitting assignments, collaborating, and receiving customized feedback. Integration of IoT into the cloud computing platform and LMS increases accessibility to education, adaptive learning and student involvement, thus, turning smart education into one of the rapidly developing applications of IoT [28], [29].

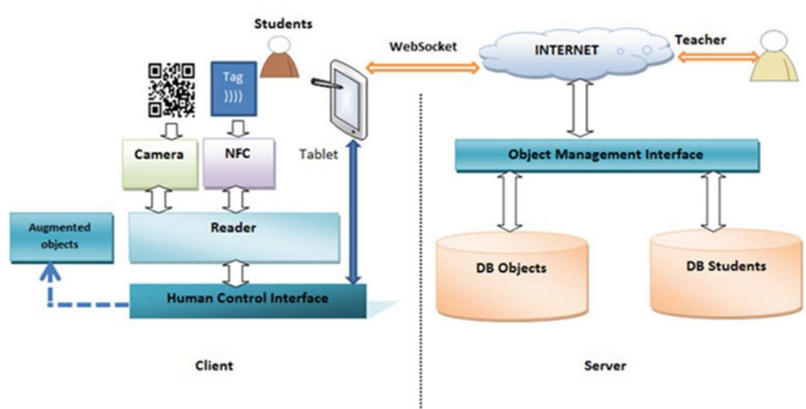

Figure.8: Architecture of the system

The IoT-assisted learning method was assessed in "Introduction to Systems Engineering" classes at the University of Córdoba, Colombia, in which students worked with learning objects empowered by IoT technology during practical lessons dealing with computer hardware. It has been found that the combination of physical objects and digital multimedia materials helps increase students' involvement in the process, conceptual understanding, and academic results. Moreover, it has been revealed that contextualized learning using the Internet of Objects contributes to meaningful learning processes, and the use of AI-driven recommender systems will make smart education even more personalized [28], [29].

B. Futuristic Smart Education Model

Introduction of the Internet of Things (IoT) has changed the face of conventional education through the creation of intelligent, connected and personalized learning systems. IoT has helped to facilitate communication between students, teachers, and infrastructure in the educational system, thus creating a collaborative environment that improves teaching and learning experience [29]. The impact of IoT on education can be classified into three broad categories, namely: stakeholders, applications and learning modes, as shown in Figure 9.

Learning modes include collaborative learning, adaptive learning, blended learning, virtual instructors and personalized education that help enhance student engagement and performance. IoT applications cover smart campuses, connected classrooms, attendance tracking, personalized learning, learning assistance to learners with special needs, and remote health monitoring. All these IoT technologies help different stakeholders such as learners, teachers, administrators, and institutions in various ways such as efficient campus management, improved classroom interaction, enhanced security, and decision making for education through data analysis. This way, embedded IoT technologies play an important role in designing intelligent and flexible education systems [28], [29].

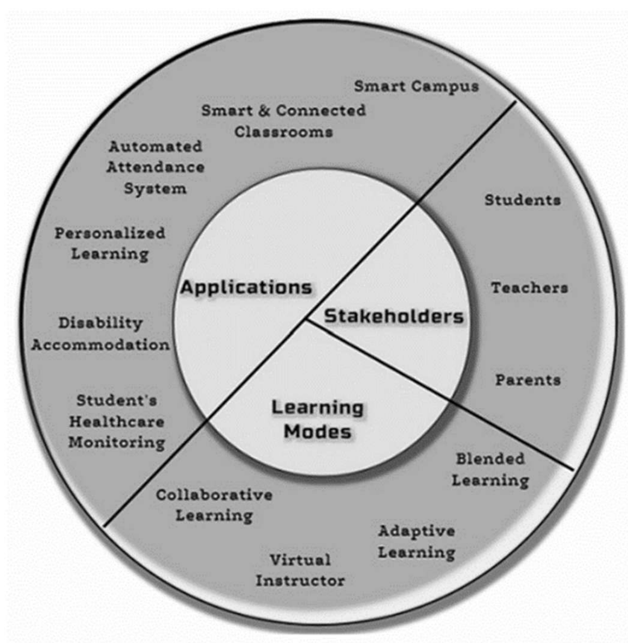

Figure.9: IoT's 3D effects on the educational model

As depicted in Figure 9, the implications of embedded IoT on education could be analyzed from three fundamental perspectives, which are learning styles, application and stakeholders. IoT technology contributes to new educational models including collaborative learning, adaptive learning, blended learning and virtual learning. The applications of IoT on education include smart campus, connected classroom, attendance system, accessibility to students with special needs, personalized learning solutions and student health management. Through the connection of educational environment, tools and users, the IoT technology makes contributions to improved campus security, streamlined management process, and better communications among students, educators and educational institutions. Thus, IoT technology is contributing to the creation of intelligent, learner-oriented educational environments [28],[29].

VII. IoT EMBEDDED SYSTEM IN AGRICULTURE

The field of agriculture continues to be one of the most significant in developing countries, as there is a need to enhance productivity, utilization, and sustainability of resources to maintain food security and development. The use of Internet of Things (IoT)-based embedded systems technology has made traditional agriculture become smart agriculture through the continuous monitoring of plants, livestock, soil, weather, and farm machinery. This is done by the fusion of embedded sensors, wireless communications, cloud computing, and analytics, which have helped in making decisions, improving crop productivity, enhancing utilization of resources, and minimizing manual work [30], [31]. The smart agriculture system comprises of IoT-based sensor, communication, cloud, and intelligent data processing technologies as shown in Figure 10.

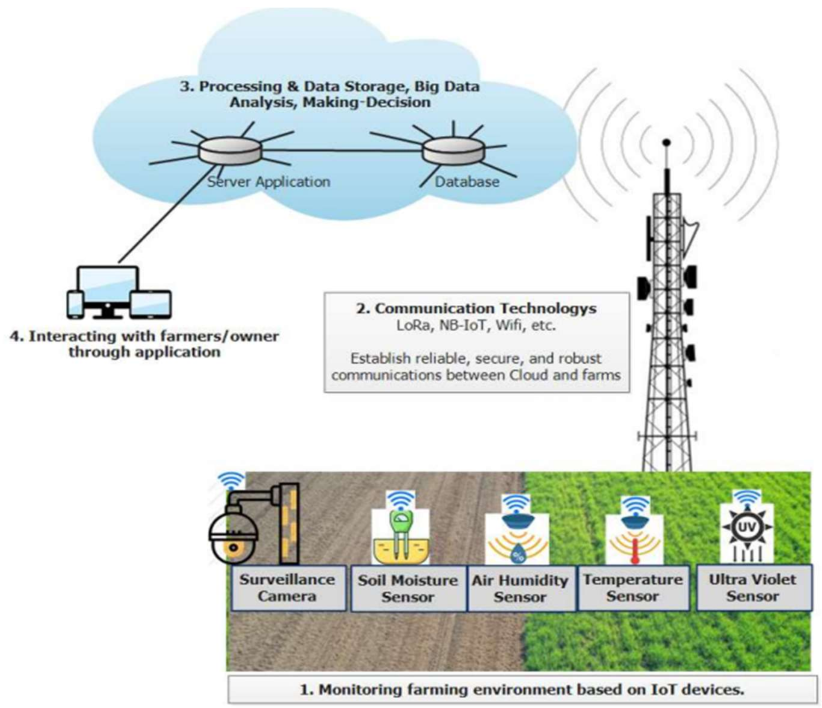

Figure.10: Smart Agriculture depicting the IoT's ecosystem architecture

The agriculture sector has been revolutionized by IoT applications like crop/livestock monitoring, smart irrigation, climate/soil monitoring, automated agricultural machinery, disease and pest control, and precision agriculture. These have enabled monitoring, resource optimization, and productivity in agriculture [30]–[39].

A. Crop Monitoring

In IoT crop monitoring, embedded sensors are used for measuring environmental and soil variables such as temperature, humidity, rainfall, soil moisture, salinity, solar radiation, and leaf wetness. Real-time monitoring allows farmers to make decisions that ensure good crop health, productivity, and quality [30], [32].

B. Tracking and Traceability

IoT is helping agricultural chains become more efficient by making it possible to track the entire chain from farm to end-user. RFID, GPS, and sensor-based traceability systems allow for efficient logistics operations and food safety [33], [34].

C. Smart Agricultural Machinery

Internet of Things-driven agricultural equipment is equipped with GPS technology, GNSS technology, and embedded sensors for autonomous control and field mapping. Smart tractors, drones, and robotics increase the efficiency of agricultural processes while providing optimum irrigation, fertilization, and resource management [31], [35], [36].

D. Smart Greenhouse

Smart greenhouses use Internet of Things technology to monitor the conditions of the environment and control irrigation, air circulation, light, and temperature. Smart greenhouses enhance the quality of produce, save energy, water resources, and minimize human involvement [32], [34], [37].

E. Precision Agriculture

Precision agriculture uses sensors, GPS, artificial intelligence, and data analysis for optimization of agricultural processes. Real-time field monitoring helps to use optimum amounts of water, fertilizers, and pesticides to increase yield while reducing the cost of operation [38], [39].

VIII. IoT EMBEDDED SYSTEM IN BUILDING SMART CITIES

Rapid urbanization has posed serious problems in relation to transportation, energy usage, sustainability, public safety, healthcare, and city service management. In order to overcome these problems, the incorporation of IoT-based embedded systems into urban infrastructure has been gaining importance, whereby sensors, actuators, communication infrastructure, cloud computing, AI, and edge computing are utilized to build smart urban infrastructure. The use of such interconnected systems is facilitating efficient and effective monitoring of urban operations and making decisions based on data analytics, improving the quality of life of citizens [40], [41].

A. Embedded IoT based Intelligent Traffic Management (ITM) system in smart cities

Intelligent Traffic Management (ITM) is among the most critical uses of embedded IoT technology within smart cities. The rising number of vehicles in urban areas has led to severe traffic congestion, increased fuel use, air pollution, high accident rates, and longer commuting time. Traditional traffic management systems have been ineffective in dealing with constantly changing traffic situations; therefore, intelligent traffic management becomes highly necessary [40].

In ITM systems powered by IoT technology, embedded sensors, surveillance cameras, GPS, RFIDs, roadside units (RSUs), and wireless communications help in collecting real-time data about traffic movement, traffic density, weather conditions, road conditions, and accidents. The data collected are analyzed using machine learning and artificial intelligence algorithms in cloud or edge computing to predict the future traffic situation. With the aid of such predictions, traffic signals are adjusted according to predicted traffic situation [40], [42].

The ITM model combines a variety of technologies such as the Internet of Things (IoT), cloud computing, artificial intelligence (AI), machine learning (ML), edge computing, and big data analysis in a multi-layered structure composed of the sensing, communication, services, and application layers. The system is equipped with various intelligent systems to track vehicles, detect accidents, analyze traffic images, and manage vehicular communications. Figure 11 shows how the embedded IoT technologies can be utilized in the proposed ITM architecture [40], [42], [43], [48].

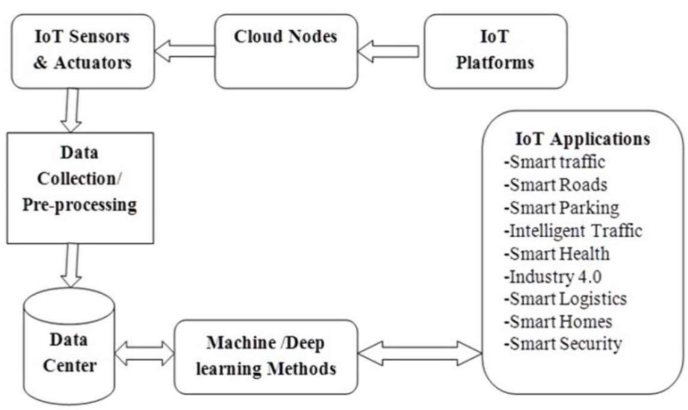

Figure.11: Application of Embedded IoT in ITM.

For evaluating the performance of the proposed framework, various scenarios with CAVs, regular cars, and mixed traffic scenarios have been analyzed. IoT sensors embedded into the system gather real-time data related to the motion of vehicles, traffic density, road and environmental conditions. Big data analytics and machine learning algorithms deployed in the cloud/edge computing platforms discover traffic patterns, identify abnormal

situations, forecast congestion, and dynamically adjust the timings of the traffic signals. The communication between vehicles equipped with wireless modules and RSUs is possible by means of V2V and V2I communications technology [42], [43], [48], [49].
According to performance evaluations, the proposed ITM framework is able to perform better than the traditional traffic management framework in terms of higher packet delivery rates, reduced communication delays, increased network throughput, and efficient coordination of traffic signals [42], [48]. The proposed framework also offers accurate localization of the vehicles, quick accident detection, dynamic congestion prediction, and intelligent navigation of the vehicles through continuous monitoring of traffic density, speed of the vehicles, and conditions of the roads. In case of heavy traffic, the vehicles are rerouted in an automated way to minimize the travel time, fuel consumption, and environmental pollution.

B. Smart City Management system

Urbanization happening at a fast pace all over the world has increased the rate of building of smart cities, where the IoT-based embedded systems have been used to ensure better performance, efficiency, and sustainability in urban services. This is possible with the use of embedded devices, sensors, actuators, smartphones, networking technologies, cloud computing, and artificial intelligence in smart city applications, which lead to the provision of constant monitoring and intelligent control of urban infrastructure [41], [44], [51].
Smart cities are ecosystems composed of a number of connected domains such as smart mobility and transport, smart energy, smart waste management, smart environment monitoring, smart security, smart homes, smart food and water management, and smart healthcare, as shown in Figure 12. This efficient connection makes it possible for the city authorities to efficiently manage their public utilities and provide services that are efficient, secure, and citizen-friendly. Moreover, IoT-powered smart city solutions assist in the development of sustainable urban development through improving service provision, minimizing energy consumption, reducing the environmental footprint, and providing immediate response to urban issues [44], [45], [51].

Figure.12: An illustration of a smart city

Smart Energy
Internet of Energy (IoE) is an evolution of IoT technology, applied to contemporary electrical power systems through incorporation of smart meters, renewable energy sources, energy storage, and intelligent communication networks. Continuous tracking of electricity production, transmission, distribution, and usage allows for energy management, demand response, and optimal electricity distribution via IoE. This helps ensure reliable operation of power grids, effective use of energy, minimizes electricity transmission losses, and makes it possible to integrate renewable energy sources on a large scale.

Smart Mobility & Transport
Innovations in IoT have revolutionized transport systems through intelligent communication between vehicles, roadside facilities, and traffic control centers. Internet of Vehicle (IoV) involves integration of connected vehicles, Global Positioning System (GPS), wireless communications, and cloud services for offering real-time traffic analysis, intelligent routing, collision warning, parking assistance, and fleet management. When used alongside artificial intelligence and edge computing, IoV will enhance transportation efficiency, road safety, and

travel experience while paving the way for connected and autonomous vehicles in future smart cities [42], [43], [48], [49].

Smart Home

The smart homes employ IoT devices which are embedded and wireless technologies such as Wi-Fi, Bluetooth, ZigBee, and others in order to automate the processes in the household. Various household devices such as smart appliances, lighting devices, cameras for home security, temperature control devices, and entertainment devices interact using centralized controllers or cloud computing platforms to enable their remote monitoring and automation. They contribute to increased energy efficiency, improved security at home, and comfort due to automatic adaptation to the needs of users [41], [52].

Smart Health

One of the most significant fields of use of IoT technologies is healthcare. Sensors that are wearable, Body Area Networks (BANs), smart medical devices, and wireless communication techniques measure heart rate, blood pressure, body temperature, blood oxygen saturation, and ECG signals. These data are safely transmitted to the cloud and analyzed there using AI technologies for disease diagnostics, remote patient monitoring, and health management. By means of IoT healthcare, healthcare becomes less expensive, accessible, useful in elderly care, and allows the continuous monitoring of chronic patients. Thus, the quality of healthcare services increases [44], [47], [52]. The field of embedded IoT continues to grow at a fast pace through diverse application areas that include transportations, health care, agriculture, education, industrial automation, and smart cities. Using intelligent sensors, wireless communication, cloud computing, edge computing, and AI, embedded IoT allows for autonomous sensing and decision making as well as resource management. Along with the growth of IoT technologies and new technologies such as 6G, digital twin, TinyML, and federated learning, embedded IoT will become more relevant as part of building sustainable, intelligent, and secure digital environments [44], [52].

Earlier sections have discussed the recent advances in embedded IoT technologies and the applications of such technologies in various fields, such as automotive, healthcare, education, agriculture, and smart cities. Such examples show how embedded IoT systems make use of sensor technology, actuators, embedded processors, communication, and intelligent control to achieve real-time monitoring and automated operation. As IoT technology advances further, it is transforming lives through greater efficiencies, connectivity, sustainability, and service quality in several sectors [44], [52].

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