ISA Journal of Engineering and Technology (ISAJET)

Homepage: https://isapublisher.com/isajet/
Email: office.isapublisher@gmail.com

Volume 2, Issue 1, Jan-Feb, 2025 ISSN: 3049-1843

Real-Time Neonatal Incubator Assistant Using IoT Technology: Design, Calibration, Implementation and Performance Evaluation

Vincent Andrew Akpan

Department of Biomedical Engineering, The Federal University of Technology, P.M.B. 704 Akure, Ondo State, Nigeria

***Received:** 01.03.2025* | ***Accepted:** 29.04.2025* | ***Published:** 24.06.2025*

***Corresponding Author:** Vincent Andrew Akpan

DOI: *10.5281/zenodo.15732042*

Abstract **Original Research Article**

An incubator is a womb-like environment for preterm infants which improve their chances of survival. Monitoring the incubator environment is crucial as it play vital role towards the growth and survival of the preterm infant. This paper presents the design, calibration, implementation and performance evaluation of a real-time neonatal incubator assistant (NIA) using Internet-of-Things (IoT) technology for monitoring the environment of a standard preterm infant incubator. The six parameters under close monitoring are: 1). temperature, 2). humidity, 3). heart beat rate per minute, 4). heat pulse per minute, 5). sound level, and 6). air quality. The proposed IoT-based NIA consist of three main systems, namely: 1). The IoT-based hardware module; 2). A web and database system; and 3). Wi-Fi wireless remote monitoring system with a software application for online monitoring of the preterm infant incubator via a mobile application (Mobile App). The satisfactory validation performance evaluations of the designed and constructed IoT-based NIA shows that it can be deployed in a hospital clinical setting for preterm infant monitoring in an incubator.

Keywords: Embedded Systems, Internet-of-Things (IoT), Neonatal Incubator Assistant (NIA), Smart Sensors.

Citation: Akpan, V. A. (2025). Real-Time Neonatal Incubator Assistant Using IoT Technology: Design, Calibration, Implementation and Performance Evaluation. *ISA Journal of Engineering and Technology (ISAJET), 2(1)*. ISSN: 3049-1843. [40-65]

1. INTRODUCTION

An estimated 13.4 million babies were born preterm in 2020 (Perin *et al*., 2022). Babies who are born alive before 37 weeks of the full gestational period are considered preterm or neonates and are likely to have higher risks for various health problems (Ohuma *et al*., 2020). Neonatal babies, also known as premature babies, are born when the mother has not reached the normal 37 weeks of pregnancy (Zivaljevic *et al*., 2024). Preterm births are usually classified under three categories based on the gestational age, namely (Ohuma *et al*., 2020; Perin *et al*., 2022): *1)*. extremely preterm (less than 28 weeks), *2)*. very preterm (28 to less than 32 weeks), and *3)*. moderate to late preterm (32 to 37 weeks).

More than 1 million deaths worldwide occur each year as a result of preterm delivery, which is a primary cause of newborn morbidity and mortality (Perin *et al*., 2022; Sasu, 2024). And the key organs of premature babies are not developed due to early birth; in which the baby's vital organs like the lungs, digestive track, and overall weight will be low when compared to those of normally born infants. The neonates have a variety of shortcomings such as temperature control, heart beats rates, light intensity as well as surrounding humidity and sound (noise) levels (Gat *et al*., 2021). A new born has a relatively large surface area, poor thermal insulation and a small mass that can act as heat sink as well as minimal ability to preserve heat by altering posture (Ha and Mendola, 2017). Thus, neonates need an environment that is exactly like that of the womb to adapt to the outside world. It is for this reason that neonates are housed in an incubator to replicate the conditions found in the womb (Gat *et al*., 2021; Ha and Mendola, 2017). The following parameter in the incubator should be maintained as follows: temperature at 36.5 – 37.5 °C (James, 2017); Humidity at 60 – 70% (James, 2017; Laurie, 2021); sound level at 45 – 50 decibels (dB) (Das *et al*., 2023); air quality at 200 – 10,000 part per million (ppm) (Lin *et al*., 2023; Ritz *et al*., 2007; WHO, 2021); heart beat rate per minute 120 – 180 bpm (Alonzo *et al*., 2018; Henslee *et al*., 1997; Kapadia *et al*., 2024); heart pulse (breathing) rate at 40

– 60 pulse per minute (NCH, 2025); blood pressure is normally an upper number (systolic) between 60 and 80, and a lower number (diastolic) between 30 and 45 (NCH, 2025).

The incubator has a lengthy historical background compared to other technological devices commonly employed in the Neonatal Intensive Care Unit (NICU). The utilization of incubators for regulating the surroundings of premature neonates can be traced back to the 1800s, during which medical professionals acknowledged the potential fatality of infants subjected to cold stress (Cone, 1981).

Jean-Louis-Paul Denuce documented the utilization of an incubator apparatus specifically engineered for caring for premature infants in the year 1857. By the late 1800s, Tarnier, an obstetrician from Paris, had repurposed chicken incubators that were initially utilized in a Paris Zoo to provide care for premature infants (Hess, 1922).

Neonatal care is a critical component of healthcare, especially in the developing world. The survival of preterm and low birth-weight infants depends on access to appropriate medical equipment and expertise (Usman *et al*., 2019). The use of an incubator is a standard treatment for preterm infants, providing the necessary temperature, oxygen, sound level, and humidity for the optimal care of these infants (Rajalakshim *et al*., 2019). Unfortunately, many hospitals in the developing world lack the resources to purchase and maintain this expensive equipment, leaving many infants at risk of mortality (Maynard *et al*., 2015). This has led to the development of Internet of Things (IoT) based neonatal incubators, designed to be more affordable and accessible in resource-limited settings (Tarouco *et al*., 2012; Thilakarathne and Kagita, 2020).

A contemporary infant incubator is a rigid, box-shaped apparatus designed to house an infant, featuring transparent sections that enable visual monitoring of the infant and mechanisms for regulating the infant's environment, primarily through the use of heated air within the enclosure. A standard neonatal incubator in the Ondo State Specialist Hospital, Akure, Ondo State, Nigeria is shown in Figure 1 (OSSH, 2025). The incubator device is typically composed of an AC-powered heating element, a fan for air circulation, a servo control mechanism for temperature regulation, a receptacle for water to introduce humidity, a control valve for administering oxygen, and nursing care access ports, as described by (Antonucci *et al*., 2009).

Figure 1: A standard neonatal incubator (Courtesy: Ondo State Specialist Hospital, Akure, Ondo State, Nigeria) (OSSH, 2025).

Several smart technologies have adapted for the development of smart incubator systems which can be classified into four categories, namely:

1). Machine Learning-Based Smart Incubators: Machine learning-based smart incubators use artificial intelligence algorithms to analyze real-time data and predict the risk of neonatal complications such as sepsis. These system can also provide early intervention and personalized care; thereby improving the overall health outcomes of preterm infants. However, there is a need for further clinical validation and standardization of these systems (Raharja, and Sugiyarta, 2022; de Araújo *et al*., 2013).

2).IoT-Based Smart Incubator: IoT-based smart incubators use Internet-connected sensors and devices to monitor and control various environmental parameters such as pressure, noise level, air quality, temperature, humidity, oxygen level, etc. these systems also have built-in alarms that alerts the medical staff if any of the parameters goes out of range. Several studies have shown that IoT-based smart incubators can improve temperature stability, reduce energy consumption and provide better noise reduction compared to conventional incubators (Adalarasu *et al*., 2020; Athimoolam and Karuppasamy, 2022).

3).Hybrid Smart Incubators: Hybrid smart incubators combine IoT technology with conventional incubators to provide a more efficient and integrated system. These systems can automatically adjust environmental parameters based on real-time data and provide advanced features such as phototherapy lights and integrated feeding systems. However, there is limited evidence on the clinical outcomes and cost-effectiveness of theses systems (Indhuja *et al*., 2023; Boyd *et al*., 2017).

4).Wearable Smart Incubators: Wearable smart incubators are a new type of incubators that can be worn by the infants, providing continuous monitoring and control of environmental parameters. These systems can improve parent-infant bonding; and thus reduce the risk of infection, and provide better mobility compared to conventional incubators. However, there are challenges in maintaining the stability and safety of wearable devices (Henderson. and McDonagh, 2017; Devaprasanth *et al*., 2022).

Smart incubators for preterm infants have the potential to improve clinical outcomes, reduce costs, and provide personalized care (Linu *et al*., 2024; Athimoolam and Karuppasamy, 2022). IoT-based smart incubators have shown promising results in temperature stability, energy consumption and noise reduction (Adalarasu *et al*., 2020; Athimoolam and Karuppasamy, 2022). Machine learning-based smart incubators have the potential to provide early intervention and personalized care, but there is a need for further clinical validation and standardization Raharja, and Sugiyarta, 2022; de Araújo *et al*., 2013. Hybrid (Indhuja *et al*., 2023; Boyd *et al*., 2017) and wearable smart incubators are new and emerging technologies that require further research and development to optimize their performance and safety (Henderson. and McDonagh, 2017; Devaprasanth *et al*., 2022). On the overall, smart incubators represent an exciting and rapidly evolving area of research in neonatal care.

The use of an IoT-based neonatal incubator has the potential to improve patient outcomes and reduce costs. This is achieved through several different components of the technology (Adalarasu *et al*., 2020; Firmansyah *et al*., 2019). First, remotely monitoring a newborn's vital signs through connected sensors allows healthcare providers to respond quickly to changes in the patient's condition. This improves the accuracy and speed of response, potentially saving lives (Issa and Thabit, 2021). The ability to monitor vital signs remotely also allows healthcare providers to manage the care of multiple patients better simultaneously, which could reduce the need for additional personnel (Ashfaq *et al*., 2022).

The ability to share information between healthcare providers and the patient’s family is another benefit of using an IoT-based neonatal incubator. Through connected devices, healthcare providers can send updates to the family regarding the patient’s condition and provide education and support (Rayan *et al*., 2021). This can help to reduce anxiety and improve communication between the healthcare provider and the family. Accessing the patient’s medical data remotely can also help reduce the need for in-person visits, which can help reduce costs (Darniss *et al*., 2022).

Additionally, using an IoT-based neonatal incubator can help improve the patient's safety by reducing the risk of medical errors. Connected medical devices can provide real-time data on the patient's condition, which can help to identify potential problems early on and prevent them from becoming severe (Keikhosrokiani, 2021). The use of connected devices also allows healthcare providers to respond quickly to patient conditions changes, which can help reduce the risk of medical errors (Issa and Thabit, 2021).

Using an IoT-based neonatal incubator can reduce expenses by eliminating the need for additional staff. With the ability to remotely monitor a patient's condition, healthcare providers can reduce the frequency of in-person visits, thereby reducing staffing costs (Kalilani *et al*., 2021). Connected devices can also reduce the need for paper records, thereby reducing the costs associated with storing and retrieving medical records (Mutanu *et al*., 2022).

2. Background Knowledge

2.1 Related Works

There have been numerous enhancements to the effectiveness and efficiency of infant incubators. (Bouattoura *et al*. 1998) proposed an active humidification system and developed an algorithm incorporating optimal control theory and dynamic programming. In addition, a temperature control system with thermistors, a combination of Pulse Width Modulation (PWM), and a straightforward ON-OFF control system was created. Since the late 20th century, microprocessors have rendered incubators more advanced. (Amadi *et al*., 2007) developed an incubator reuse technique (RIT). (Tisa *et al*., 2013) designed an enhanced temperature control system with thermistors as temperature sensors and a combination of Pulse Width Modulation (PWM) and an ON-OFF control system. These developments of the 21st century have enhanced the emphasis on improved neonatal incubator designs. In addition, (Huang *et al*., 2015) designed and implemented an intelligent control for neonatal incubators to address the issues of cost and lack of spare parts in resource-poor settings. Recent innovations in the design of incubators include incorporating IoT systems for direct communication between the doctor and mother with the incubator (Huang *et al*., 2015).

Sahoo and co-worker (Sahoo *et al*., 2014) created an incubator with wireless alert transmission to a neonatal nursing station. This system consists of four distinct units: the incubator temperature monitor and control unit, the body temperature monitoring unit, the bed damp monitoring unit, and the alarm transmission unit. The temperature is measured by the incubator's internal LM35 temperature sensor, and this signal is then received by the USB4704 and controlled by LabVIEW. The ON-OFF logic is utilized to generate the control signals, which are generated via USB4704. Using the same USB4704 device, the body temperature was also measured. A circuit that utilizes a 5V power supply to detect bed moisture. The alarm signal for detecting unjust conditions within these circuits is then transmitted to a distant nursing station.

The work of Kshirsgar and co-workers (Kshirsgar *et al*., 2019) presented a framework for multipurpose temperature monitoring and neonatal control incubators. The incubator used a DHT11 sensor to detect temperature and humidity; the DHT11 sensor controls a cooling fan to maintain the optimal temperature inside the incubator. The battery section is used to provide power to the incubator. Sensors for monitoring the infant’s heart rate and respiration rate are attached. IoT transmits the vital sign parameters' output to the LCD or a server. The system is Wi-Fi enabled so that a specialist can remotely monitor and control the surrounding area's temperature. Heartbeat and respiration sensors were attached to monitor the infant’s respiration rate, and the system was connected to Wi-Fi to enable remote monitoring and control of the surrounding temperature.

In another development, Fahmi *et al*., (2020) proposed the prototype of an Internet-based infant incubator monitoring system equipped with a variety of sensors and components, including Biosensors (heart rate and body temperature sensors), Environment monitoring sensors (ambient temperature, humidity, and gas), sound sensors, LCD, and speaker. Using artificial intelligence, these sensors and other components send data to the server and mobile applications to monitor the baby's voice for the following conditions: burpy, hungry, pain, sleepy, and uncomfortable.

According to Mageshkumar and Tamilsevan (2022), an infant incubator should monitor the temperature relative humidity and light intensity while keeping them constant, giving the neonates an environment that mimics the womb. Abd.Kloliq and Ali (2021) discuss the cost-effective design of an embedded device for in-utero newborn baby monitor in real-time with only temperature and humidity monitors. Zaylaa *et al.* (2018) on the other hand attempted to improve the functionality and power management of the standard incubator monitoring system to offer remarkable reliability and flexibility. However, Akant *et al*. (2017) suggested that an incubator should be a system that continuously monitors and gathers data on the preterm’s health with such data transmission to the doctor via Bluetooth device. Furthermore, Mageshkumar *et al*. (2020) proposed a design and constructed a closed-loop system for constant monitoring and regulating the temperature and humidity together with the oxygen and light levels within a neonatal incubator using a PID controller and an Arduino Uno microcontroller.

Neonatal incubators utilizing IoT technology have emerged as a viable solution to the challenge of providing better care for newborn infants (Martinez *et al*., 2023). Developing and deploying an IoT neonatal incubator presents numerous safety, cost, and usability challenges. Modern technologies combined with IoT has revolutionized the design, construction, and deployment of healthcare solutions (Islam *et al*., 2015; Dang *et al*., 2019; Taroucoet *al*., 2012; Thilakarathne and Kagita, 2020; Akpan and Olawale, 2024).

2.2 Architecture of the Internet of Things Framework

The IoT is an evolving technology transforming human interactions with their surroundings. The IoT is a paradigm shift representing innovation in the information and communication technology (ICT) industry (Dang *et al*., 2019). The IoT is an open and extensive network of sentient objects that can self-organize and share information, data, and resources, react, and act in response to situations and environmental changes (Madakam *et al*., 2015).

IoT ecosystems comprise Web-enabled smart devices that employ integrated systems, such as processors, sensors, and communication hardware, to compile, transmit, and act upon the data they collect. The architecture of the IoT framework is illustrated in Figure 2. IoT devices make the sensor data they collect accessible through an IoT entry or another peripheral device. (Gaber *et al*., 2018) The data is sent to the cloud or on-premises for analysis. These devices periodically exchange messages with other connected devices and take action based on the information they obtain from one another. Machines perform most work without human intervention, but they can be configured, given instructions, and given access to data (Zhou *et al*., 2019). The IoT applications of these web-enabled devices significantly impact their connectivity, networking, and communication protocols.

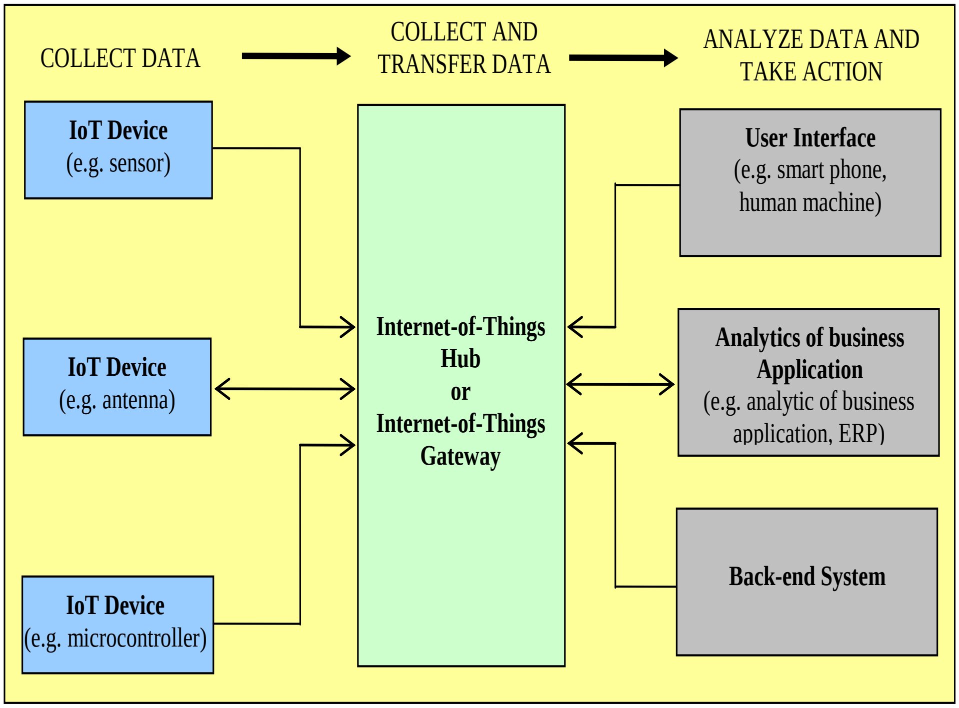


Figure 2: Architecture of the IoT framework.

The Internet of Things has the potential to enhance the accessibility, efficacy, and cost-effectiveness of healthcare. Healthcare is one of the industries with the highest growth rates worldwide. The Internet of Things enables remote patient monitoring and diagnosis, allowing physicians to perpetually monitor their patient's vital signs and other health indicators. Patients with chronic conditions may benefit most from this because they can be monitored remotely, saving time and money by avoiding frequent medical visits. IoT can increase the precision of diagnosis and treatment since data collected from sensors can be analyzed to swiftly and precisely identify health issues (Yuehong *et al*., 2016).

A critical IoT tool is cloud computing which is a model that facilitates Internet-based on-demand access to shared computing resources. Remote servers hosted by third-party providers enable users to store, process, and access data and applications. It saves businesses money by only paying for cloud services (Sunyaev, 2020). It also makes it easy to test new ideas and design new applications without regard to hardware constraints.

In the design of IoT-based system, several key factors must be considered during data streaming, data communication protocols, and security protocols. Data streaming allows real-time monitoring and analysis of the patient's vital signs (El-Aziz *et al*., 2021). Data streaming requires reliable data communication protocols such as Bluetooth Low Energy (BLE), Wi-Fi, and Zigbee. BLE is a popular choice for medical device applications due to its low power consumption and reliable data transmission. Wi-Fi is also popular, as it provides a high data rate and long-range communication. Zigbee is a cost-effective protocol suitable for low-power applications (Shahzad and Oelmann, 2014).

IoT-based systems uses secure protocols such as transport layer security (TLS) and Internet Protocol security (IPSec) to protect against data breaches. TLS is a popular protocol for encrypting data in transit; while IPSec is a protocol for securing data at rest. The communication protocols should also support authentication and authorization of devices as well as user authentication protocols such as open authorization (OAuth) and unique identifier (OpenID Connect, OIDC) to ensure secured user authentication (Suresh *et al*., 2014; Zhou *et al*., 2021). The system should use secure protocols such as hypertext transfer protocol secure (HTTPS) and advanced encryption standard (AES) to protect data from unauthorized access.

2.3 IoT in Healthcare Technologies

2.3.1 Recent Trends of IoT in Healthcare

The IoT has the potential to revolutionize the healthcare sector by connecting medical devices, patients, and healthcare providers in a seamless network (Islam *et al*., 2015; Dang *et al*., 2019; Tarouco *et al*., 2012; Thilakarathne and Kagita, 2020). IoT in healthcare refers to the use of interconnected devices and sensors to monitor and manage patient's health remotely, allowing for real-time tracking of vital signs and other health data. IoT can enable proactive and individualized care which has the potential to enhance patient outcomes, boost operational efficiency and lower costs in the healthcare industry. The recent trends of IoT deployments in healthcare are illustrated in Figure 3. The critical IoT deployments in healthcare include but not limited to the following:

1). Remote Patient Monitoring: IoT devices can remotely monitor vital signs like blood pressure, oxygen levels and heart rate, giving medical practitioners the ability to maintain tabs on patient's health and take the necessary actions as needed (Iranpak *et al*., 2021).

2).*Wearable Health Technology:* Wearable devices, such as smart watches, can track physical activity, sleep patterns and other health metrics; and thus, providing patients with real-time feedback on their health status (Surantha *et al*., 2021; Henderson. and McDonagh, 2017; Devaprasanth *et al*., 2022).

3). *Medication Adherence:* IoT-enabled pill bottles can remind patients to take their medication at the appropriate time and track whether they have taken their medication as prescribed (Islam *et al*., 2023).

4). *Hospital Efficiency:* IoT smart sensors can monitor equipment usage, inventory and patient flow; and thus, help hospitals optimize their operations and reduce cost (Ahmad, 2024).

5). *Telehealth:* IoT can enable remote consultation and virtual visits with healthcare providers, allowing patients to receive medical care from the comfort of their homes (Dike and Jackson, 2024).

Figure 3: Recent trend in IoT deployment in healthcare.

2.3.2 Challenges in Implementing an IoT-based Neonatal Incubators

Recently, the emergence of IoT technology has revolutionized smart incubators for preterm babies. IoT-enabled smart incubators can currently offer real-time monitoring of the infant's environment from anywhere in the world; thus, allowing healthcare professionals to provide better healthcare and treatment (Athimoolam and Karuppasamy, 2022; Linu *et al*., 2024). Today, there are several types of smart incubators, including open-care system, closed-care system, and transport incubators. Each type of incubator has its own unique features, benefits and challenges but they all share the common goal of providing a safe and optimal environment for preterm babies.

Using Internet of Things (IoT) technology to develop an IoT-based neonatal incubator can revolutionize how neonatal care is provided. This is because IoT-based incubators can wirelessly collect and exchange data to monitor the newborn's health and ensure that they receive the best care possible (Rayan *et al*., 2021). However, some several key challenges must be addressed to implement an IoT-based neonatal incubator successfully.

1). *Security:* The security of an IoT-based neonatal incubator is paramount, as any breach could compromise sensitive patient information. Furthermore, any failure in the security of the incubator could result in the loss of vital patient data and even the disruption of the device itself (Witti *et al*., 2018). As such, it is essential to ensure that the device is adequately secured, with secure communications protocols and authentication methods in place to prevent unauthorized access. Additionally, the device should be regularly monitored to detect potential threats or vulnerabilities and be patched to address any identified security issues (Vermesan and Friess, 2014).

2). *Data privacy:* The data collected by an IoT-based neonatal incubator is sensitive and must be protected to ensure the patient's privacy. As such, it is essential to ensure the device is adequately secured to prevent any unauthorized access or misuse of the data (Mutanu *et al*., 2022). Additionally, the data should be encrypted to ensure it is not accessible to unauthorized parties. Furthermore, ensuring that the data is only shared with authorized parties and that any third-party service providers are subject to a data privacy agreement (Elhoseny *et al*., 2021).

3). Data storage: The data collected by a neonatal incubator utilizing the Internet of Things must be stored securely to ensure its safety and integrity. As a result, it is crucial to ensure that the data is stored in a secure and dependable environment with sufficient backup and disaster recovery procedures. In addition, the data must be stored following applicable laws and regulations (Jegadeesan *et al*., 2019).

4). Cost: The cost of an IoT-based neonatal incubator is an essential factor that must be considered. As such, it is vital to ensure that the device is cost-effective and that any additional costs associated with it are justified by its benefits (Vermesan *et al*., 2022). Additionally, it is essential to ensure that third-party service providers are cost-effective and that their services can provide a return on investment.

5). Ethical Issues: There are still ethical concern around the use of incubators, particularly in cases where the cost of care was prohibitively expensive. This led to the question about the appropriate allocation of resources and the potential for disparities in healthcare based on socio-economic status (Alamneh *et al*., 2022).

3. Overview of the Proposed Real-Time Neonatal Incubator Assistant Using IoT Technology

The proposed neonatal incubator assistant (NIA) comprises three main components, namely: *1).* The IoT-based hardware module; *2).* A web and database subsystem; and *3).* Wi-Fi wireless remote monitoring system with a software application (App) as illustrated in the block diagram of Figure 4. The hardware module has been configured to independently obtain data from various sensors embedded in the NIA. Remote monitoring applications refer to tools that enable users to obtain processed data in real time via mobile applications on android phones or personal computers.

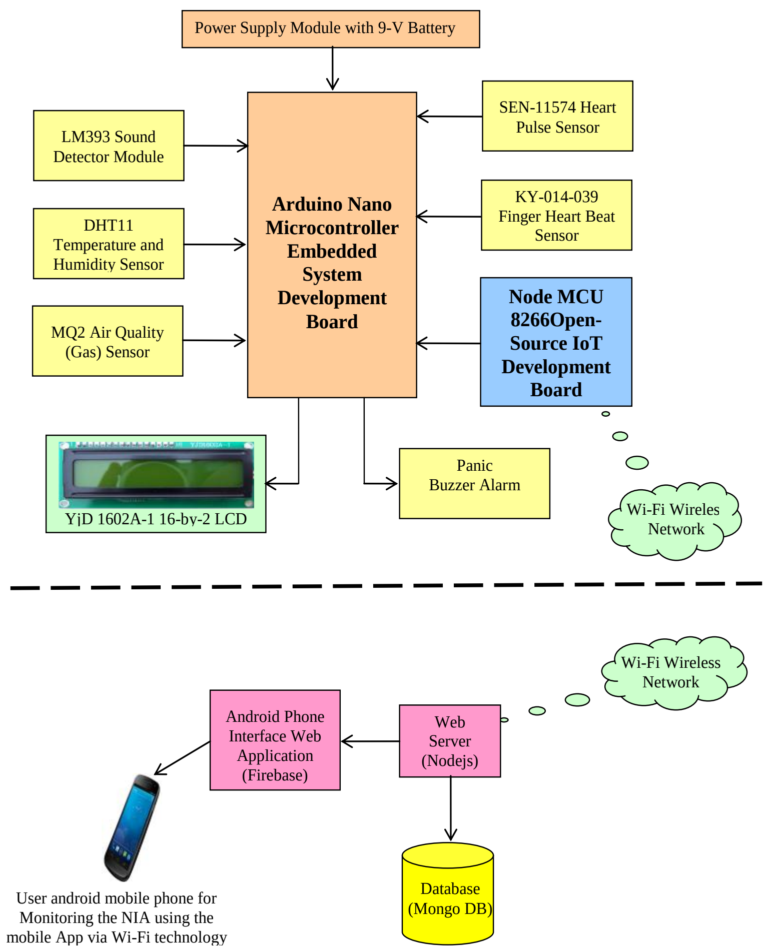


Figure 4: Block diagram of the proposed real-time neonatal incubator assistant using IoT technology.

The hardware module of the proposed neonatal incubator assistant (NIA), as illustrated in topmost part of Figure 4, consist of five sensors, namely: *1).* LM393 sound detector module to measure the sound level in the incubator; *2).* DHT11 sensor to measure both the temperature and relative humidity within the incubator; *3).* MQ2 gas sensor for measuring the air quality within the incubator; *4).* KY-014-039 finger heart beat sensor to measure the heart beat of the preterm infant in the incubator; and *5)*. SEN-11574 heart pulse sensor for measuring the pulse rate of the preterm infant in the incubator. The electronic buzzer is triggered “ON” whenever the measured values of any of the six parameters in the incubator violates, either below or above, the threshold value set for each sensor.

The data is subsequently processed by the Arduino Nano microcontroller in conjunction with the NodeMCU ESP8266 microcontroller and transmitted via the Nodejs web server to the Android phone interface web Application (App) and the MongoDB database for storage through the Internet. The Wi-Fi technology supports the data communication mechanism between the IoT-based hardware module and the web and database subsystem as well as the remote web application using Firebase software. The status of the six neonatal incubator measurable parameters can then be view via an android phone hosting the web application (App).

4. Materials, Design Methodology and Construction of the Real-Time Neonatal Incubator Assistant Using Internet-of-Things (IoT)Technology

4.1 Materials for the Neonatal Incubator Assistant

The major materials required for the construction of the real-time neonatal incubator monitoring device using IoT technology are: *(i)* Finger heartbeat (KY-014-039) sensor, *(ii)* Heart pulse (SEN-11574) sensor, *(iii)* Node Micro-controller ESP8266 (NodeMCU ESP8266) Open-source IoT platform , *(iv)* DHT11 temperature and humidity sensor, *(v)* MQ2 air quality gas Sensor, *(vi)* YJD 1602A-I 16-by-2 LCD display module, *(vii)* Sound detector module, *(viii)* Sound detector module with LM393 sensor and microphone, *(ix)* Electronic buzzer, *(x)* Arduino Nano real-time embedded system development board, *(xi)* Firebase mobile and web application development platform, *(xii)* Web server (Nodejs), *(xiii)* Database (Mongo DB) *(xiv)* Samsung A02 android mobile phone, *(xv)* DatexOhmeda Light Portable S/5 monitor, *(xvi)* M3 Plus heart health monitor, *(xvii)* Y5 smart bracelet pulse monitor, *(xviii)* S8607 sound level meter, *(xix)* Loovett professional air quality tester.

4.2 Design of the Neonatal Incubator Assistant

This section describes the design of the IoT-based neonatal incubator assistant (NIA). The design phase consists of the hardware and software components. Included in this work are environmental sensors detect and measure conditions such as temperature, humidity, sound detection module, light, barometric pressure, water level, indoor/outdoor air quality, and air pollutants (Ho *et al*., 2005).Biosensors are analytical instruments that detect and quantify the presence of a specific substance or analyze a sample by employing a biological recognition element and a physicochemical detectors. The finger heartbeat sensor and heart pulse sensor are examples of biosensors used in this work. While often used interchangeably, heart rate and pulse rate refer to distinct, though related, measures. Heart rate is the number of times the heart beats per minute; while pulse rate is the number of times the arteries expand and contract with each heartbeat (Redcliff Labs, 2025).

4.2.1 Hardware Components of the NIA

4.2.1.1 Arduino Nano (ANH, 2025)

The Arduino Nano is Arduino’s classic breadboard friendly designed board with the smallest dimensions. The Arduino Nano comes with pin headers that allow for an easy attachment onto a breadboard and features a Mini-B USB connector.

The Arduino is an open-source hardware design with software development kit (SDK) for their versatile IoT controller. The Arduino hardware is a microcontroller board with a USB connector, LED lights, and standard data pins. It also defines standard interfaces to interact with sensors or other boards. The Arduino board have different types of CPU chips (typically an ARM or Intel x86 chip) with memory chips, and a variety of programming environments. However, the flexibility of Arduino also means significant variations across different vendors. For example, most Arduino boards do not have WiFi capabilities, and some even have a serial data port instead of a USB port.

4.2.1.2 NodeMCU ESP8266 (NMCU, 2025)

The NodeMCU (*N*ode *M*icro*C*ontroller *U*nit) is an open-source software and hardware development environment built around an inexpensive System-on-a-Chip (SoC) called the ESP8266. The ESP8266 contains the crucial elements of a computer: CPU, RAM, networking (WiFi), and even a modern operating system and software development kit (SDK) which makes the NodeMCU ESP8266 an excellent choice for Internet of Things (IoT) projects of all kinds.

However, as a chip, the ESP8266 is also hard to access and use; soldering with wires is necessary to the appropriate analog voltage as well as to its pins for the simplest tasks such as powering it on or sending a keystroke to the “computer” on the chip. Furthermore, the NodeMCU ESP8266 must be programmed in low-level machine instructions that can be interpreted by the chip’s hardware. This level of integration is not a problem using the ESP8266 as an embedded controller chip in mass-produced electronics.

4.2.1.3 DHT11 Temperature and Humidity Sensor (DTH, 2025)

The DHT11 sensor is a commonly used temperature and humidity sensor. The sensor comes with a dedicated negative temperature coefficient (NTC) to measure temperature with an 8-bit microcontroller to output the values of temperature and humidity as serial data. The sensor is also factory calibrated and hence easy to interface with other microcontrollers. The sensor can measure temperature from 0 °C to 50 °C and humidity from 20% to 90% with an accuracy of ±1 °C and ±1%.

The data pin is connected to an input/output (I/O) pin of the MCU and a 5K pull-up resistor is used. This data pin outputs the value of both temperature and humidity as serial data. Interfacing the DHT11 sensor with Arduino is supported by ready-made libraries for immediate implementation.

The output given out by the data pin is in the order of 8-bit humidity integer data with +8-bit the Humidity decimal data, +8-bit temperature integer data, +8-bit fractional temperature data, and +8-bit parity bit. To request the DHT11 module to send these data the I/O pin has to be momentarily made low and then held high.

4.2.1.4 SEN-11574 Heart Pulse Sensor (HPS, 2025)

The SEN-11574 Pulse Sensor is a well-designed plug-and-play heart-rate sensor for Arduino. It can be used by students, artists, athletes, makers, and game & mobile developers who want to easily incorporate live heart rate data into their projects. The sensor clips onto a fingertip or earlobe and plugs right into Arduino with some jumper cables. It also includes an open-source monitoring app that graphs your pulse in real time. The heart rate sensor measures your heart rate in Beats per Minute using an optical LED light source and an LED light sensor. The light shines through your skin, and the sensor measures the amount of light that reflects back. The light reflections will vary as blood pulses under your skin past the light. The variations in the light reflections are interpreted as heartbeats.

4.2.1.5 KY-014-039 Finger Heartbeat Sensor (KYHS, 2025; KYS, 2025)

The KY-014-039 is a Low cost Heart beat Sensing Module. This Heart beat detection module uses bright infrared (IR) led and a photo-transistor to detect the pulse of the finger, a red led flashes with each pulse. Pulse monitor works as follows: the led is Turned ON on one side of the finger, and photo-transistor is on the other side of the finger. The photo-transistor used to obtain the flux emitted, when the blood flows through the finger then the resistance of the photo-transistor will be vary slightly. This module is ideally suited to adding heartbeat sensing to your project. This detection module combines a phototransistor and IR LED, which when a finger is placed between will provide a varying signal. Reading this analog signal you can interpret a change in signal as a heartbeat. Please note this is a sensitive module and will experience noise from household lights and other sources as such minimizing light to the unit will help with obtaining readings.

4.2.1.6 LM393 Sound Level Sensor (SLSM, 2025)

LM393 Microphone Sound Sensor Module. The microphone sound sensor, as the name says, detects sound. It gives a measurement of how loud a sound is.

4.2.1.7 MQ2 Air Quality Sensor (AQS, 2025; MQ2, 2025)

MQ2 gas sensor is an electronic sensor used for sensing the concentration of gases in the air such as LPG, propane, methane, hydrogen, alcohol, smoke and carbon monoxide. MQ2 gas sensor is also known as chemiresistor. It contains a sensing material whose resistance changes when it comes in contact with the gas. This change in the value of resistance is used for the detection of gas.

MQ2 is a metal oxide semiconductor type gas sensor. The concentrations of gas in the MQ2 is measured using a voltage divider network present in the sensor. This sensor works on 5V DC voltage. It can detect gases in the concentration of range 200 to 10000 ppm. Voltage values are higher when the concentration of gas is high.

4.2.2 Software Components of the IoT-based NIA

4.2.2.1 Arduino Integrated Development Environment (Arduino IDE) (AIDE, 2025)

The Arduino Integrated Development Environment (Arduino IDE) contains a text editor for writing code, a message area, a text console, a toolbar with buttons for common functions and a series of menus. It connects to the Arduino hardware to upload programs and communicate with them. The Arduino IDE is used to write the computer codes and upload the codes to the Arduino board. The Arduino IDE is very simple and this simplicity is probably on of the main reason Arduino has become so popular.

Arduino is an open-source and accessible platform for creating embedded systems. It comprises a programmable hardware circuit board (a microcontroller) and an IDE (Integrated Development Environment). This application is used to write and upload computer code to a tangible board. According to (Akpan and Eyefia, 2021; Akpan *et al*., 2019; Akpan *et al*., 2021), the programming language utilized by the Arduino IDE is a simplified variant of C++, thereby rendering the programming process more accessible to comprehend. The Arduino IDE was also used in writing and uploading the codes used to implement the NodeMCU ESP8266.

4.2.2.2 Firebase Software

Firebase is a mobile and web application development platform that provides numerous tools and services for constructing, testing, and deploying applications. Firebase's real-time database, which enables real-time data synchronization across multiple devices and platforms, is one of its most essential features. This can be advantageous for programs requiring real-time updates, such as messaging programs and collaborative work tools.

In addition to its core features, Firebase offers various supplementary services, including cloud messaging, which facilitates the dissemination of messages and notifications to users across diverse platforms. The provision of authentication services enables developers to incorporate user authentication and authorization into their applications conveniently.

Furthermore, Firebase offers cloud storage solutions for both user-generated content and application data, alongside hosting services that facilitate the deployment of web applications. Additional functionalities encompass analytics, crash analysis, and experimentation with A/B testing (Khawas and Shah, 2018).

4.2.2.3 Restful App (Nodejs)

NodeJS is a JavaScript based virtual runtime environment used to implement RESTful APIs or web servers (Nodejs, 2025; PJSF, 2025). This tool was selected due to its flexibility, rich tooling and support library, and most importantly speed and scalability compared to PHP based XAMPP servers. This tool was also preferred because it utilized the JavaScript programming language which will be inevitably utilized in the development of the Web interface, thus avoiding the need to use multiple programming languages. The NodeJS executable was downloaded from the NodeJS official website and installed according to the instructions provided there (Akpan and Olawale, 2024).

4.2.2.4 Database (MondoDB)

MongoDB is a NoSQL database (i.e. Not only Structured Query Language database) which in contrast to SQL databases (Structured Query Language database) utilizes a document model rather than the table model. The document model stores every record as a document, each with unique indexing identification, and structures all related document in a collection. It also allows the creation of relationships between documents in an easy way. This method makes MongoDB a faster and even more scalable choice compared to the SQL databases (Akpan and Olawale, 2024).

4.2.3 The Designed and Constructed IoT-Based Neonatal Incubator Assistant

The circuit for the proposed IoT-based NIA was designed using Proteus software as shown in Figure 5. The proposed IoT-based NIA was constructed and wired manually. The designed and constructed IoT-based NIA is shown in Figure 6. The overall integration of the IoT-based NIA is coordinated by the Arduino Nano embedded system development board. The complete software program for the implementation and control of the IoT-based NIA through the Arduino Nano board is given in the Appendix I of this paper.

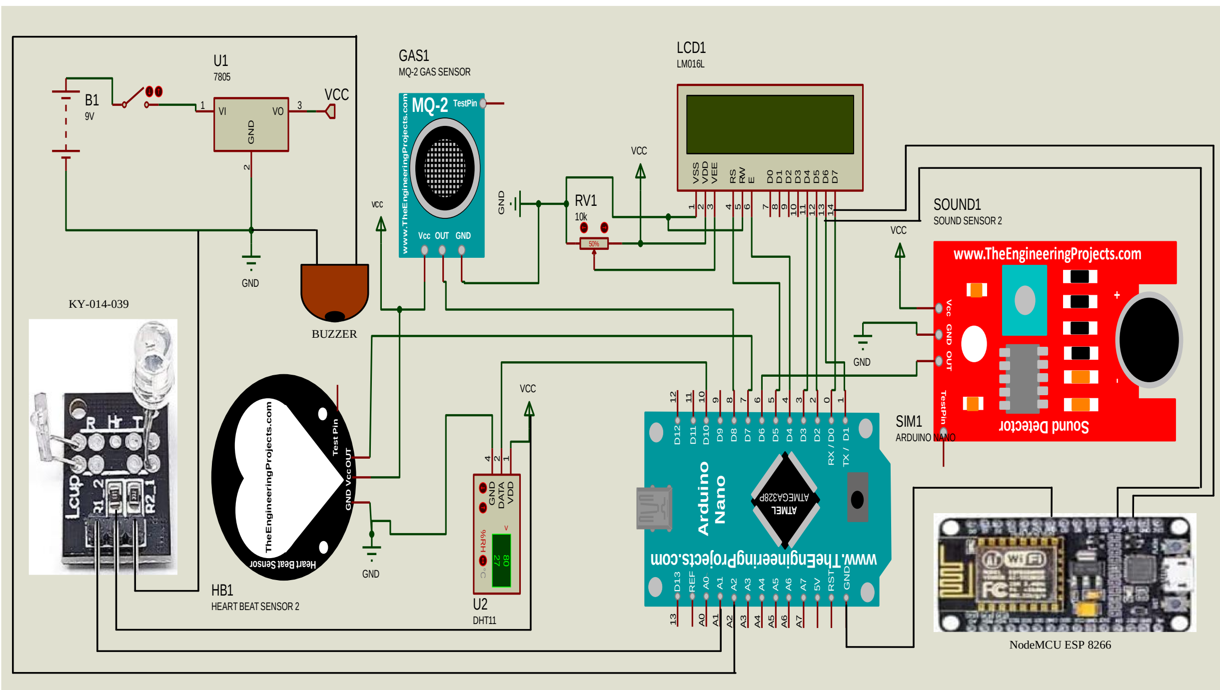


Figure 5: The circuit diagram of the proposed for the real-time monitoring of neonatal incubator assistant using IoT technology.

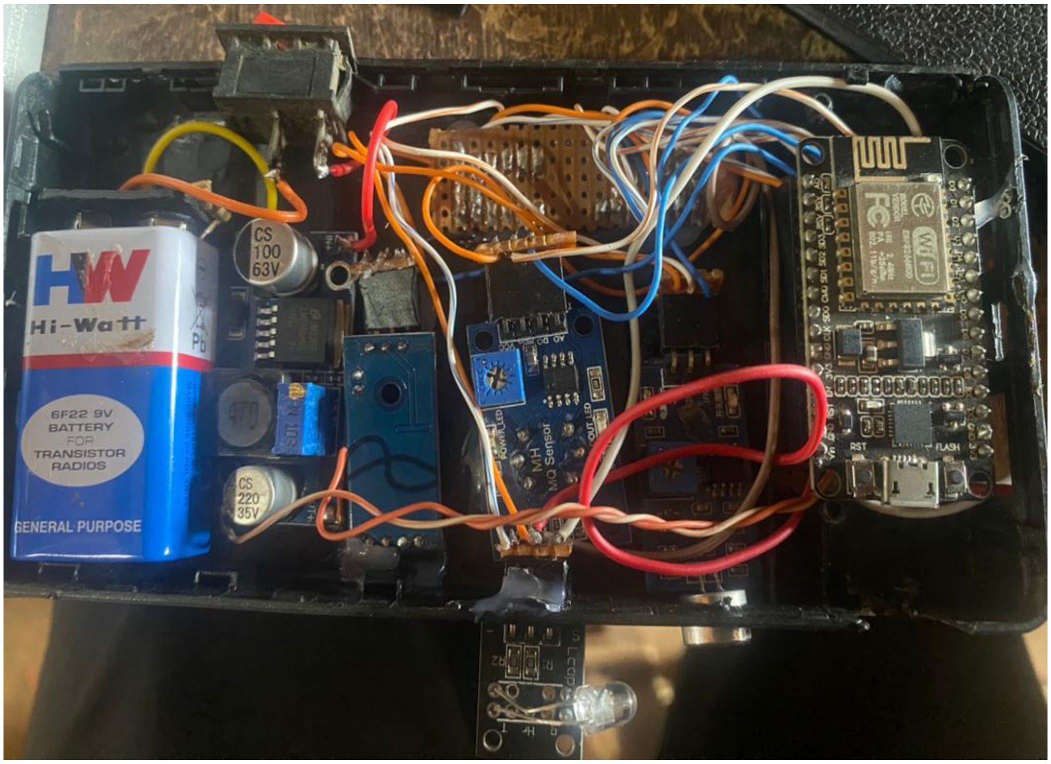


Figure 6: The designed and costructed neonatal incubator assistant.

4.3 Callibration of the IoT-Based Neonatal Incubator Assistant Sensors

For the consistency, accuracy and proper functioning of the proposed IoT-based neonatal incubator assistant (NIA), the designed and constructed IoT-based NIA in Section 4.2.3 as shown in Figure 5 and Figure 6 was calibrated against standard equipment and devices.

The DHT11 temperature and humidty sensor was calibrated against the Datex-Ohmeda S/5 portable patient monitor. The calibration of the DHT11 sensor for temperature and humidity measurements was done through programminge using the Arduino IDE. The Datex-Ohmeda S/5 light portable monitor is capable of measuring both temperature and humidity simultaneously (DOLP, 2025). The lower and upper threshold temperature values were set to the recommended values of between 36.5 and 37.5 °C respectively while the recommended lower and upper threshold of the humidity were set 60 and 70% respectively.

The SEN-11574 heart pulse sensor was calibrated against the standard Y5 Smart Bracelet Pulse monitoring device. The lower and upper threshold values for the SEN-11574 sensor were set to the recommended values of between 40 and 60 pulse per minute respectively. The calibration of the SEN-11574 sensor for heart pulse measurements was done through programminge using the Arduino IDE with a standard Y5 smart bracelet heart pulse monitoring device.

The KY-014-039 finger heartbeat sensor was calibrated against the standard M3 Plus Wristband Heart Health Monitor for monitoring heart beat per minute. The lower and upper threshold values for the KY-014-039 finger heartbeat sensor were set to the respective recommended values of 120 and 180 beat per minute. The calbration of the KY-014-039 finger heartbeat sensor was done pregrammatical using the Arduino IDE with a standard M3 Plus heart health monitoring device.

The LM393 sound level detector module adjusted to the prescribed level through the 10-kΩ variable resistor present on the module by turning the trimmer knob counter-clockwise to increase the sensitivity to 50 dB as shown in Figure 7 (Admin, 2025). The LM393 sound level detector module was then calibrated against the standard S8607 Portable Digital Sound Level Meter using software through the Arduino IDE.

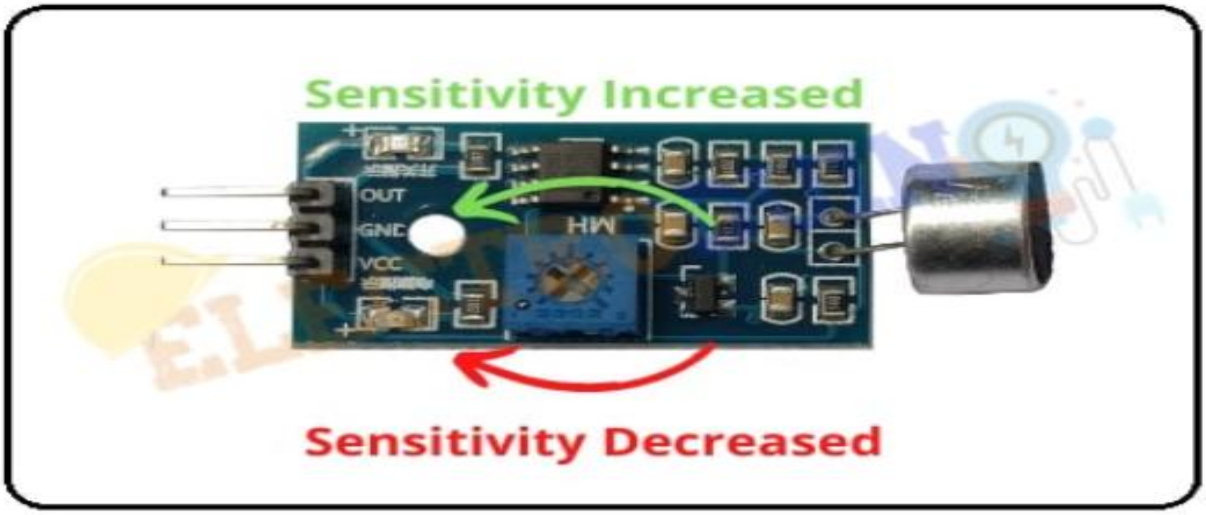


Figure 7: Sensitivity control for the sound sensor adjustment (Admin, 2025).

The MQ2 gas sensor was calibrated for air quality measurement using the Loovett professional indoor air quality monitor 5-in-1 portable smart air quality tester. The lower and upper threshhold of the MQ2 sensor was set to between 200 and 10,000 ppm respectively to detects gases in the concentration of range from 200 to 10,000ppmrange because toxic gas poese a serious threat to the health of the neonate. The calbration of the MQ2 sensor was done pregrammatical using the Arduino IDE toegther with a standard Loovett Professional air quality tester.

4.4 Mobile Application (App) Development for the Neonatal Incubator Assistant using the Firebase

The mobile web application for remote monitoring of the preterm infant incubator is developed using the Firebase software. The following steps are taken to navigate the Firebase admin user interface:

Step 1): Log in to the Firebase account at the Firebase console website (console.firebase.google.com) as shown in Figure 8(a).

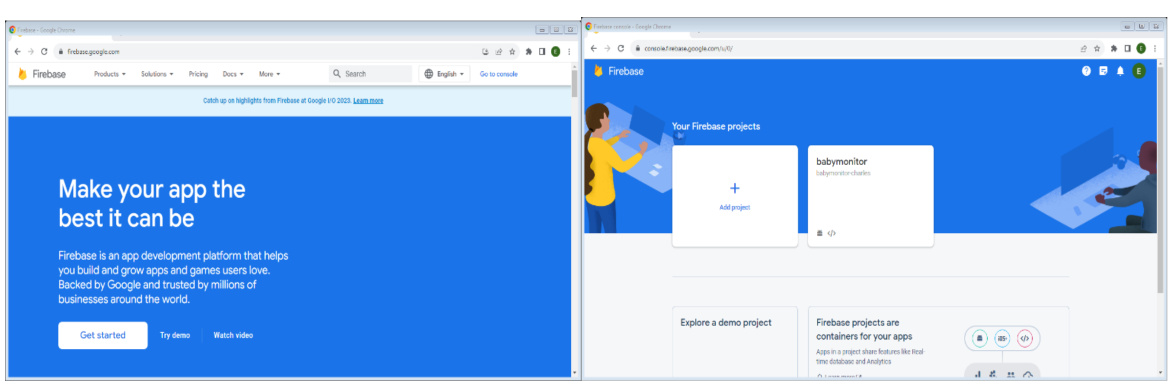
Step 2): The Firebase console dashboard is opened after the login. This is the main page where the APP "Baby Monitor" can be accessed as shown in Figure 8(b).

Step 3): On the menu bar in the left-hand corner is the project overview. It shows the different firebase sections as shown in Figure 8(c).

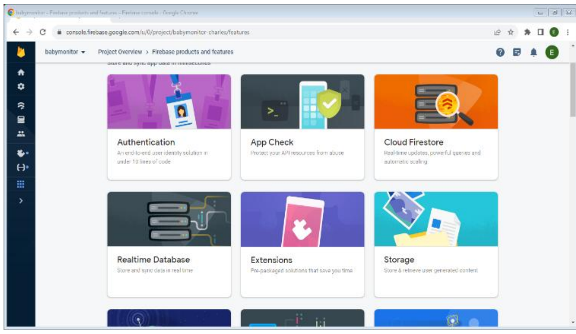
Step 4): Clicking on the "see all features" option fills the entire sections, and the "real time database" is clicked. The real-time database: provides and sync data in real-time as shown in Figure 8(d).

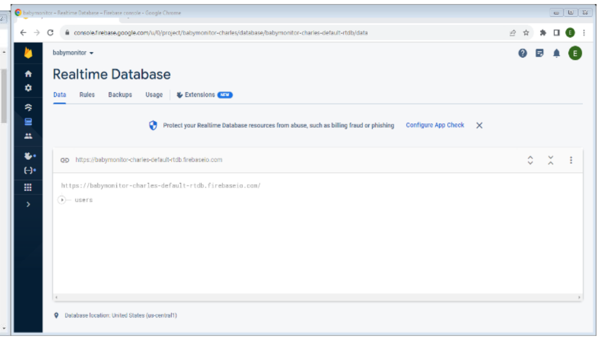
Step 5): Then click on the "real-time database, "which directs to a dashboard showing the "users icon" as shown in Figure 8(e).

Step 6): Clicking on the "users icon" provides a "123" tab, which displays the results in real-time as shown in Figure 8(f).

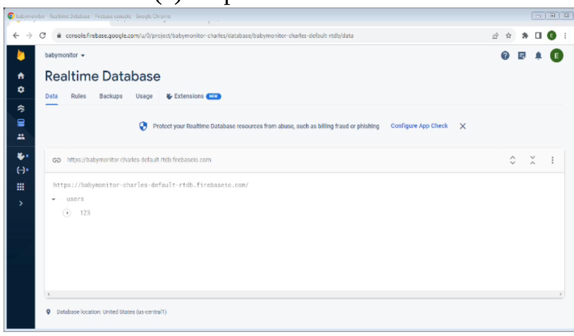


(a) Step 1 (b) Step 2





(c) Step 3 (d) Step 4



(e) Step 5 (f) Step 6

Figure 8: Step-wise directions for logging on to the Firebase App for the proposed system for real-time monitoring of neonatal incubator using IoT technology.

4.5 Implementation and Operation of the Constructed Neonatal Incubator Assistant

The design and constructed IoT-based neonatal incubator assistant was tested after calibration as discussed in Section 4.3 and the web application deployment using the Firebase described in Section 4.4.

Due to light weight and ease of shaping, plastic is used in the casing of the designed and constructed IoT-based NIA for neonatal incubators as shown in Figure 9; thus, making the plastic an ideal material for casing the IoT-based NIA that can fit perfectly into the standard preterm infant incubator as shown in Figure 10.

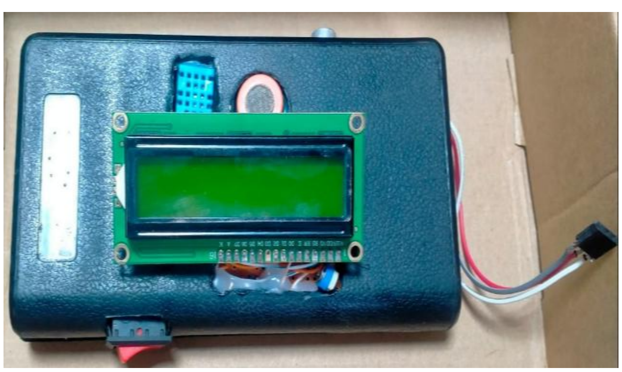
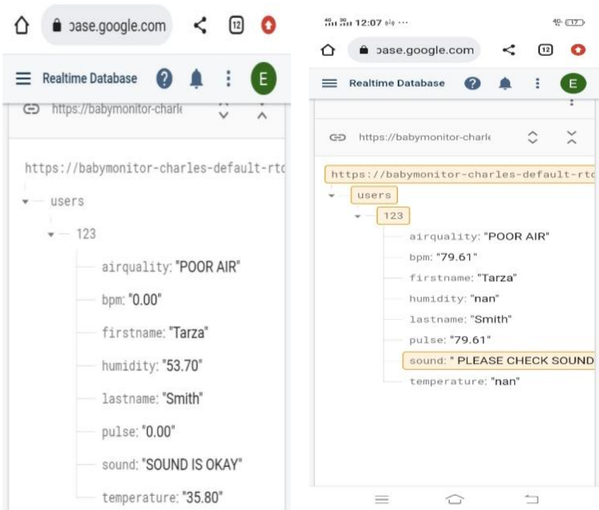


Figure 9: The photograph of the designed, constructed and cased IoT-based neonatal incubator assistant for real-time monitoring of preterm infant neonatal incubator.

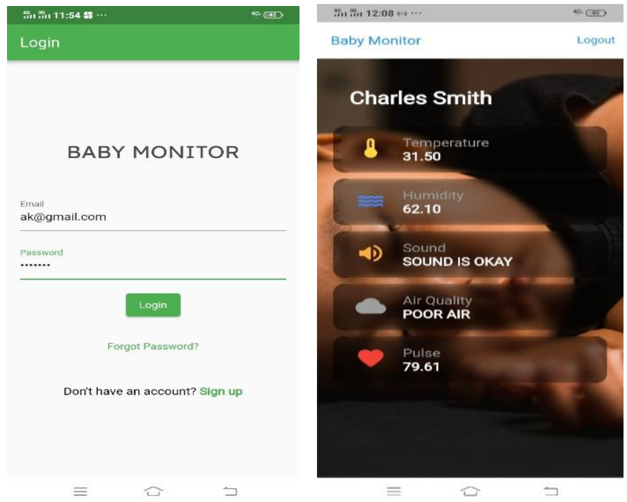
Figure 10: Integration of the IoT-based neonatal incubator assistant with a standard preterm infant incubator in Ondo State Specialist hospital, Akure, Ondo State, Nigeria.

The results of the preliminary implementation and operation of the designed and constructed IoT-based neonatal incubator assistant on a desktop computer is shown in Figure 11. The successful implementation and operation of the designed and constructed IoT-based neonatal incubator assistant is verified via the web application displayed on android phone A02 Samsung screen as shown in Figure 12.



(a) (b)

Figure 11: Preliminary results of the implementation and operation of the IoT-based neonatal incubator assistant on desktop computer.



(a) (b)

Figure 12: Web interface login interface for the neonatal incubator assistant (NIA) monitor App: (a) login interface and (b) NIA web App on android phone.

5. RESULT AND DISCUSSIONS

Correlation is a statistical measure that expresses the extend to which two variable or set of data are linearly related. In a physical sense, correlation describes the degree to which two variables tend to change together. A positive correlation means that as one variable increases, the other also tends to increase. Conversely, a negative correlation indicates that as one variable increases, the other tends to decrease.

Standard deviation is a measure of how spread out or dispersed a set of data is around its mean (average). The standard deviation quantifies the average distance each data point is from the mean, effectively showing the typical deviation from the average. A low standard deviation indicates data points are clustered tightly around the mean, while a high standard deviation indicates they are more spread out.

The Bland-Altman plot is a graph that shows the agreement between two quantitative measurements to visually validate data and display results to evaluate their agreement or disagreement based on the evaluation of the Bland-Altman parameters which includes ULoA as the Upper Limit of Agreement, UCI as Upper Confidence Intervals, MCI as Mean Confidence Intervals, LLoA as Lower Limit of Agreement and LCI as Lower Confidence Intervals as well as the Mean Differences (MD) between two corresponding set of measurements.

All the results presented and discussed in the Section were processed, analyzed numerically and simulated using MATLAB & Simulink® software (MathWorks, 2025).

5.1 Results

To validate the accuracy of the designed and constructed IoT-based neonatal incubator assistant (NIA), the six measureable parameters of the IoT-based NIA were calibrated against a standard devices as discussed in Section 4.3. Fifteen samples of measurements were taken each for the six measureable parameters, namely: *1).* temperature, *2).* humidity, *3).* heart beat rate per minute, *4).* heat pulse per minute, *5).* sound level, and *6).* air quality. The results of these measurements are shown in Tables 1 to 6 respectively for the six measurable parameters of the IoT-based NIA. The corresponding graphs of the calibration of these six measurable parameters against their respective standard measuring devices as shown in Figures13(a), 14(a), 15(a), 16(a), 17(a) and 18(a) respectively. The correlation coefficients, absolute mean errors and standard deviations between the measurements obtained from the standard measuring (calibration) devices and measurements obtained using the design and constructed IoT-based NIA are shown in table 7 for each of the six measurable parameters.

The corresponding Bland-Altman graphs for the calibrated six IoT-based NIA sensors against their respective standard measuring devices are shown in Figures13(b), 14(b), 15(b), 16(b), 17(b) and 18(b) with their respective LLoA, ULoA, UCI, LCI and MCI as well as the mean differences of these measurements.

Table 1: Preterm infant incubator temperature measurements using the Datex-OHMEDA patient monitor and the IoT-based neonatal incubator assistant (NIA).

S/N	OHMEDA incubator temperature (ºC)	Infant Temperature (ºC) Using IoT-based NIA
1	36.70	36.69
2	36.50	36.60
3	36.20	36.10
4	36.30	36.30
5	36.90	36.85
6	36.50	36.50
7	36.95	36.96
8	36.40	36.50
9	36.50	36.50
10	36.40	36.30
11	36.30	36.40
12	36.20	36.20
13	36.87	36.88
14	36.30	36.20
15	36.70	36.68

Table 2: Preterm infant incubator humidity measurements using the Datex-OHMEDA patient monitor and the neonatal incubator assistant (NIA)

S/N	OHMEDA Incubator Relative Humidity (%)	Infant Incubator Humidity (%) Using IoT-based NIA
1	68.00	68.50
2	69.50	69.70
3	60.00	60.50
4	60.00	60.60
5	65.00	64.50
6	69.80	69.70
7	70.00	69.50
8	62.00	62.00
9	67.60	67.70
10	65.00	64.50
11	64.00	64.50
12	68.90	68.90
13	69.00	68.50
14	68.00	67.50
15	69.30	69.30

Table 3: Preterm infant heart beat measurements using M3 plus heart health monitoring device and the IoT-based neonatal incubator assistant (NIA)

S/N	Infant heart beat per minute (bpm) using M3 Heart Health Monitor	Infant Heart Beat Per Minute (bpm) Using IoT based NIA
1	158.4	158.5
2	155.8	155.8
3	155.7	155.6
4	155.6	155.7
5	158.7	158.6
6	158.6	158.5
7	158.4	158.4
8	157.9	158.2
9	158.8	158.7
10	157.9	157.8
11	158.3	158.4
12	158.5	158.5
13	158.7	158.7
14	158.6	158.5
15	158.9	159.0

Table 4: Preterm infant heart pulse measurements using Y5 smart bracelet pulse monitor device and the IoT-based neonatal incubator assistant (NIA).

S/N	Infant Pulse Per Minute (ppm) using Y3 Smart Bracelet	Infant Heart pulse per minute (ppm) Using IoT-based NIA
1	58.6	58.7
2	56.7	56.9
3	57.8	57.8
4	58.4	58.5
5	57.9	58.0
6	58.3	58.1
7	58.9	58.9
8	56.8	56.7
9	56.9	57.0
10	57.8	57.8
11	57.9	57.8
12	58.5	58.4
13	58.3	58.4
14	58.4	58.5
15	58.2	58.2

Table 5: Preterm infant incubator sound level measurements using S8607 sound level meter and the IoT-based neonatal incubator assistant (NIA)

S/N	Incubator Sound level (dB) using S8607 Sound Level Meter	Incubator Sound Level (dB) Using IoT-based NIA
1	47.5	47.6
2	48.7	48.6
3	47.6	47.6
4	49.4	49.5
5	48.6	48.5
6	48.5	48.5
7	48.2	48.3
8	47.9	47.8
9	48.3	48.3
10	49.5	49.6
11	49.4	49.5
12	48.9	48.8
13	48.8	48.8
14	47.6	47.5
15	47.4	47.5

Table 6: infant incubator air quality measurements using Loovett professional air quality tester and the IoT-based neonatal incubator (NIA)

S/N	Incubator Air Quality (ppm) using Loovett Air Quality Tester	Incubator Air Quality (ppm) Using IoT-Based NIA
1	687	685
2	690	692
3	660	658
4	670	670
5	680	688
6	685	688
7	689	688
8	680	678
9	690	688
10	665	663
11	660	660
12	675	673
13	680	678
14	678	678
15	684	684

Table 7: Correlation coefficients, mean errors and standard deviations between standard measurements and IoT-based NIA

S/N	Incubator Parameters	Correlation Coefficients	Absolute Mean Errors	Standard Deviations
1	Temperature	0.9916	0.0080	0.2543
2	Humidity	0.9428	0.0200	0.4293
3	Heart beat per minutes	0.9820	0.0020	0.6492
4	Heart pulse per minute	0.9972	0.0067	0.1384
5	Sound level	0.9912	0.0067	0.1906
6	Air quality	0.9843	0.2667	0.8432

Table 8: Bland-Altman plot parameters evaluation between measurements from standard devices and IoT-based NIA

S/N	Incubator Parameters	ULoA	UCI	MD	MCI	LLoA	LCI
1	Temperature	0.09509	0.05247, -0.13770	0.008000	-0.01661, - 0.03261	-0.07909	-0.1217, -0.03647
2	Humidity	0.69900	0.34710, -1.05100	0.020000	-0.22310, -0.18310	-0.7390	-1.0910, -0.38710
3	Heart beat per minutes	0.23210	0.12830, -0.33590	0.020000	-0.03994, -0.07994	-0.1921	-0.2959, -0.08832
4	Heart pulse per minute	0.16650	0.08177, -0.25130	-0.006670	-0.05561, -0.04227	-0.1799	-0.2466, -0.09511
5	Sound level	0.17990	0.09511, -0.05561	0.006667	-0.04227, -0.05561	-0.1665	-0.2513, -0.08177
6	Air quality	2.45200	1.12100, -3.78200	-0.266700	-1.03500, -0.50140	-2.9850	-4.3160, -1.65500

DISCUSSION OF RESULTS

Based on the tables obtained from the calibration of the six measurable parameters of the IoT-based NIA shown in Tables 1 to 6, the corresponding graphs drawn from the Tables are shown respectively in Figures13(a), 14(a), 15(a), 16(a), 17(a) and 18(a) respectively. By inspection, it is evident from these graphs that the measured values using the IoT-based NIA closely follow the values obtained using the standard measuring devices. Further justification of the performance of the IoT-based NIA follows from the correlation coefficients, absolute mean errors and standard deviations between the measurements obtained from the standard measuring devices and measurements obtained using the design and constructed IoT-based NIA as shown in table 7. All the correlation coefficient results in the 3rd column of Table 7 tend to 1 which indicates good positive correlation between the two sets of measurements. The absolute mean errors obtained numerically as shown in the 4th column of Table 7 closely follow the mean differences (MD) of the Bland-Altman plots as can be seen in the respective Figures 13(b) through 18(b) for the six measurable parameters. The low standard deviation obtained numerically as shown in the 5th column of Table 7 indicates that the data points are clustered tightly around the mean which validates the accuracy the measurements obtained using the IoT-based NIA which is also in agreement with those obtained using the six standard measuring devices.

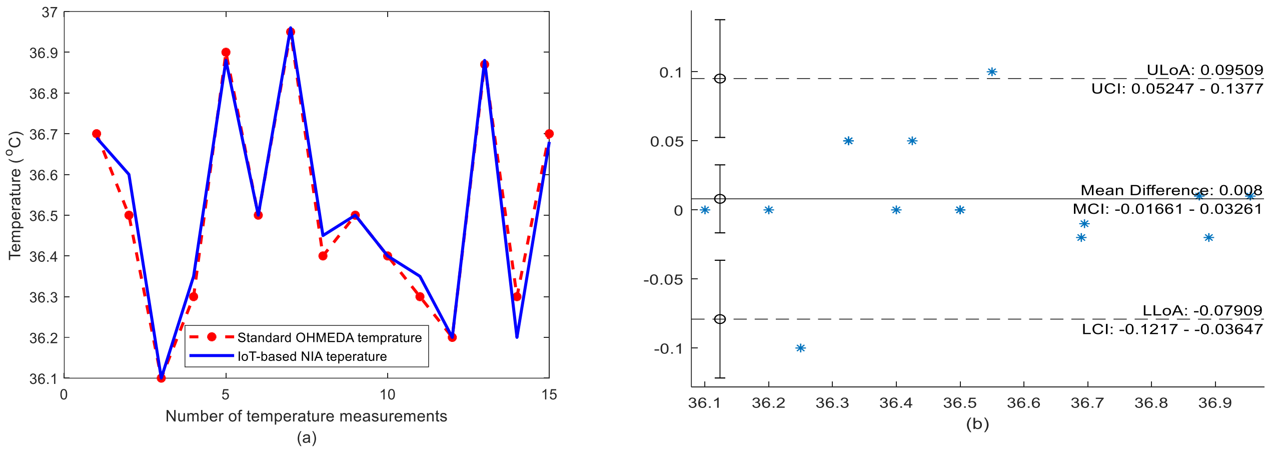


Figure 13: (a) Comparison of the temperature variations between a standard Datex-OHMEDA and the IoT-based NIA and (b) Bland Altman graph of humidity measurements from standard OHMEDA with the constructed device.

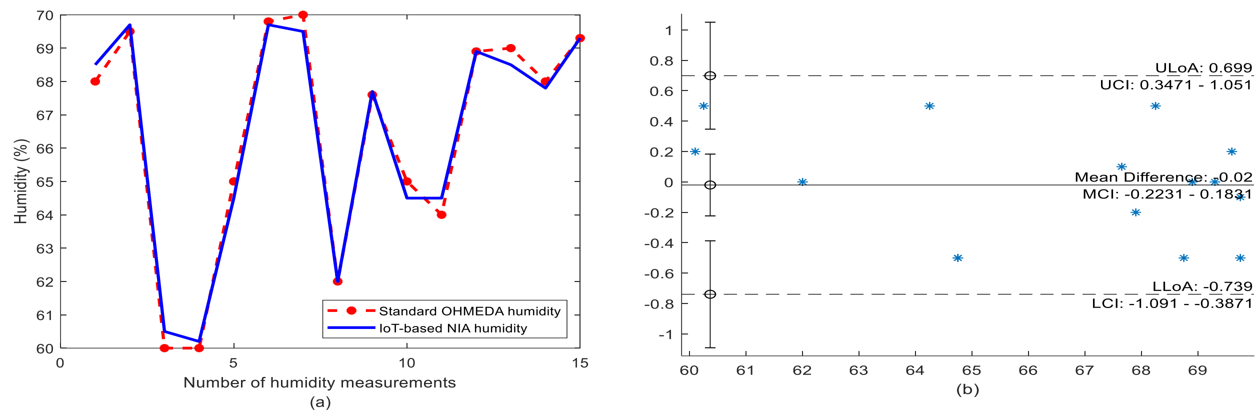


Figure 14: (a) Comparison of the humidity variations between a standard Datex-OHMEDA and the IoT-based NIA and (b) Bland Altman graph of humidity measurements from standard Datex-OHMEDA with the IoT-based NIA.

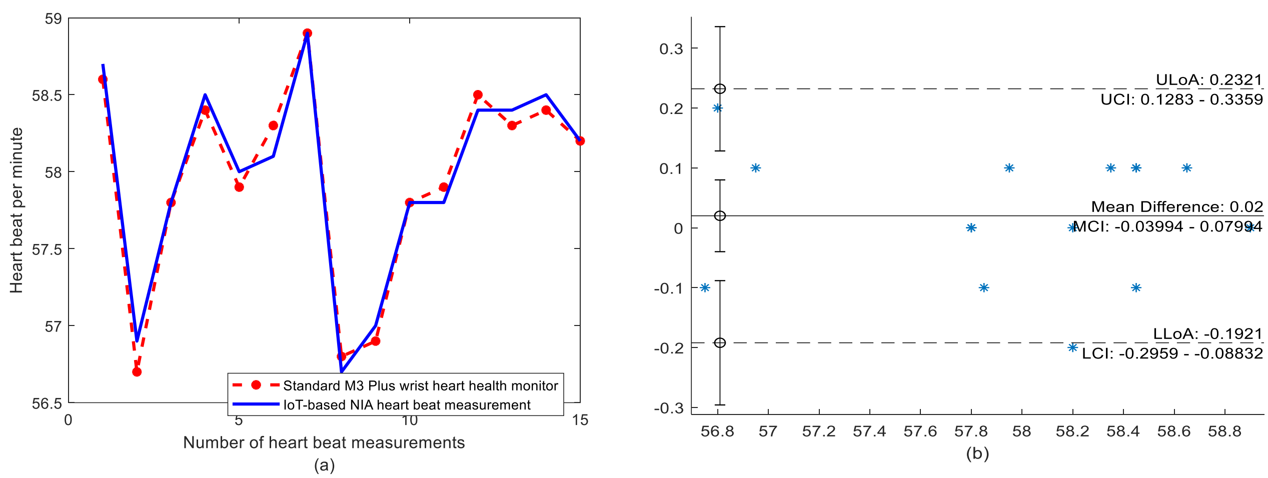


Figure 15(a): Comparison of the heart beat variations between a standard M3 heart monitor device and IoT-based NIA and (b) Bland Altman graph of heart beat measurements from standard M3 heart monitor device and IoT-based NIA.

As a further validation of the IoT-based NIA, the Bland-Altman plots for the measurements obtained using the designed and constructed IoT-based NIA versus the standard measuring devices for the six measurable parameters shown in Figures13(b), 14(b), 15(b), 16(b), 17(b) and 18(b) shows perfect agreement between the two quantitative measurements. The essence of this validation are to visually check the data, validate and display the corresponding results which evaluate the levels of agreement as shown in Table 8.

The Bland-Altman plot is a graph that shows the agreement between two quantitative measurements (see Table 8) to visually check data, validate and display results to evaluate the respective agreements. The mean differences between the two data set for each of the six measurable parameters are listed in the 5th column of Table 8 with their respective standard deviations shown in the 5th column of Table 7 are in line within the 95% of 1.96 Bland-Altman threshold benchmark. Furthermore, according to the Bland-Altman threshold benchmark, the standard deviations shown in the 5th column of Table 7 are far below the 95% of 1.96 which is an indication of good agreement between each of the two measurements for the six measurable parameters. Both the absolute mean errors of Table 7 and the mean differences of Table 8 are all around zeros which further justify good agreement for each of the two respective set of measurements without over-estimation (above zero) or under-estimation (below zero). As evident in Figures 13(b) to 18(b), the upper limit of agreement (ULoA) and lower limit of agreement (LLoA) shown in the 3rd and 7th columns of Table 8 are respectively the mean differences plus or minus 1.96 times the standard deviations of the differences which is an indication of good agreements between each of the two measurements for the six measurable parameters. These narrow limits of agreement (LoA) indicate better agreement between the two set of measurements for each of the six measureable parameters.

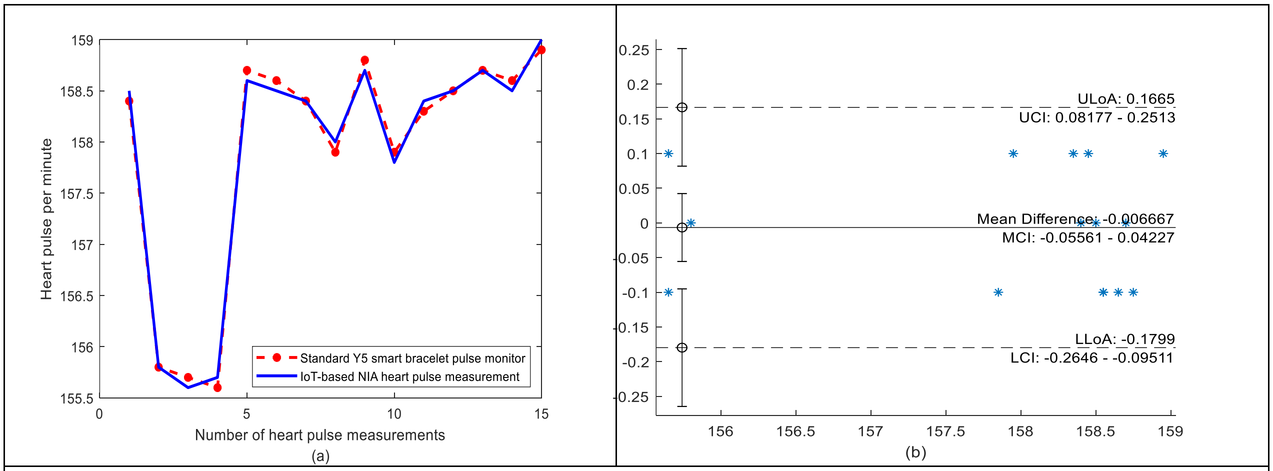


Figure 16(a): Comparison of the pulse rate variations between a standard Y5 smart pulse monitor and the IoT-based NIA and (b) Bland-Altman graph of humidity measurements from standard Y5 smart pulse monitor with the IoT-based NIA.

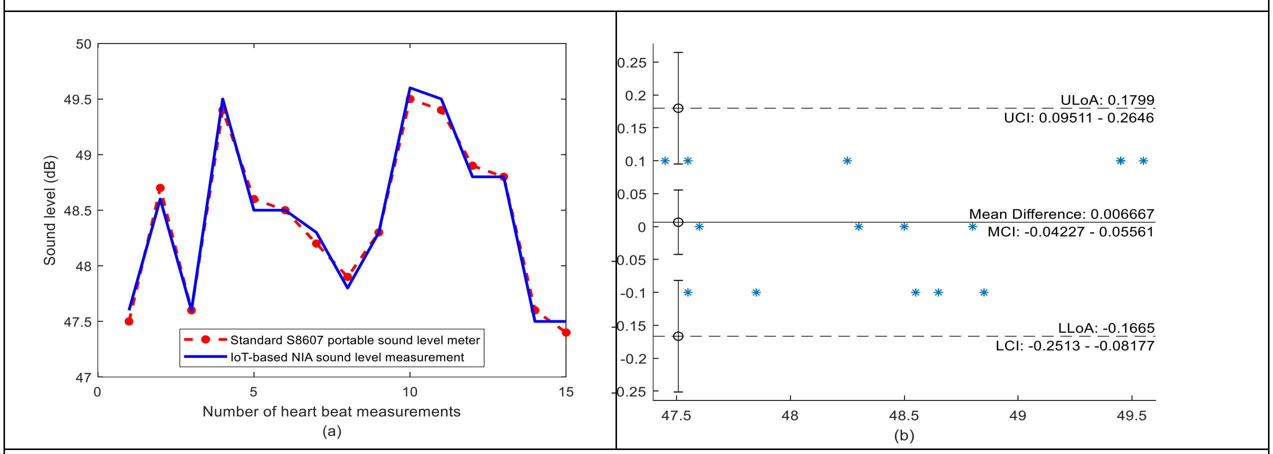


Figure 17(a): Comparison of the sound level variations between a standard S8607 sound level meter the IoT-based NIA and (b) Bland-Altman graph of humidity measurements from standard S8607 sound level meter with the IoT-based NIA.

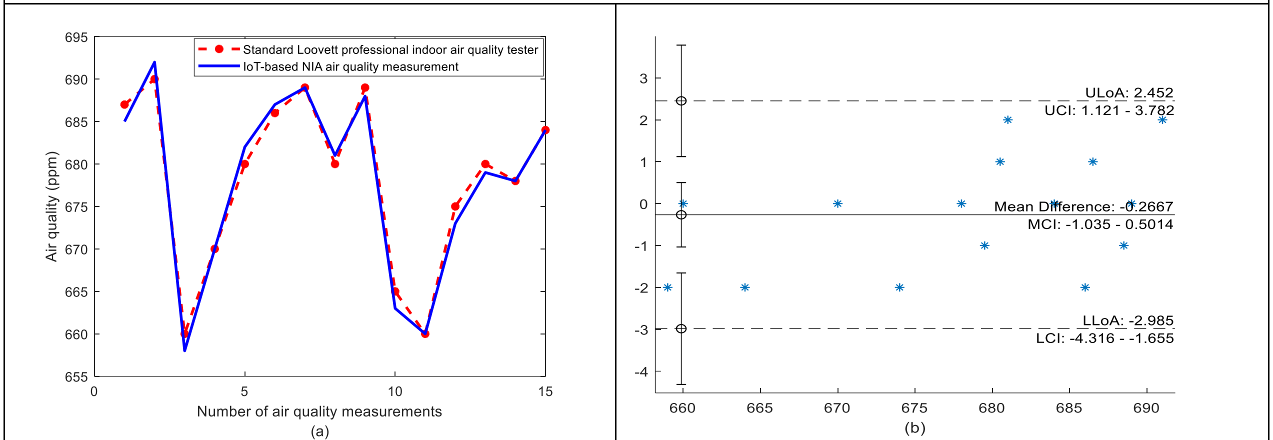


Figure 18(a): Comparison of the air quality variations between a standard Loovett air quality tester and the IoT-based NIA (b) Bland-Altman graph of humidity measurements from standard Loovett air quality tester with the IoT-based NIA.

These upper confidence interval (UCI), mean confidence interval (MCI) and lower confidence intervals (LCI) provide a measure of the precision of these values that aids in the interpretation of the Bland-Altman plots. It is evident that the UCI, MCI and LCI values shown in the 4^{th}, 6^{th} and 8^{th} column of Table derived from the Bland-Altman plots of Figure 13(b) to 18(b) justifies the precision of the designed and constructed IoT-based NIA for use in preterm infant incubator.

6. CONCLUSION AND FUTURE DIRECTIONS

The real-time neonatal incubator assistant using Internet-of-Things technology is an innovative device that continuously monitors the preterm infant incubator environment and sends the real-time incubator's environmental parameters to the cloud for storage and analysis. This data can be accessed from mobile phones and computers; thus, allowing clinicians and caregivers to take necessary action based on the information received together with the alarm from the electronic buzzer which alerts medical personnel for prompt attention to the preterm infant baby. By monitoring the preterm infant baby health parameters such as the temperature, humidity, heart rate, pulse rate, sound level and the air quality with the incubator; the preterm infant baby health status can be closely monitored for improved health condition.

Future research could focus on implementing echocardiogram (ECG) monitoring, controlling oxygen supply as well as increasing the number of biosensors and environmental sensor for improved preterm infant and incubator monitoring. Replacing the dry cell battery used in this work with a dual solar-powered and electricity system for power efficiency is encouraged.

Acknowledgement

The author wish to acknowledge Mr. Charles Ekene Mbanuzue and Mr. Oluwafemi Elisha Hassan of the Department of Biomedical Engineering, FUTA for their technical and financial supports as well as their criticism, testing and analysis of the neonatal incubator assistant that lead to the timely completion of this project.

REFERENCES

Abd.Kloliq, L. and M. Ali, M. (2021). "A Low Cost Baby Incubator Design Equipped with Vital Sign Parameters," *International Journal of Electronics, Electromedical and Medical Informatics (IJEEEMI)*, vol. 3, no. 2, pp. 53 – 58. Available: DOI:10. 35882/ijeeemi.v3i2.3.

Adalarasu, K., Harini, P., Tharunika, B. and Jagannath, M. (2020). "*IoT-Based Advanced Neonatal Incubator. In Security and Trust Issues in Internet of Things*," pp. 109 – 121. CRC Press, New York, U.S.A.

Admin (2025). Sound Sensor Module | How its work? ElectroDuino. Retreived February 20^{th}, 2025. Available: HYPERLINK "https://www.electroduino.com/sound-sensor-module-how-its-work/" https://www.electroduino.com/sound-sensor-module-how-its-work/ .

Ahmad, A. (2024). "Enhancing Hospital Efficiency through IoT and AI: A Smart Healthcare System," *Journal of Computer Science Application and Engineering*, vol. 2, no. 2, pp. 34 – 38.

AIDE (2025). "Arduino Integrated Development Environment (Arduino IDE)," Retrieved February 28^{th}, 2025. Available [Online]: HYPERLINK "https://docs.arduino.cc/software/ide-v1/tutorials/Environment/" https://docs.arduino.cc/software/ide-v1/tutorials/Environment/ .

Alamneh, T. S., Teshale, A. B., Yeshaw, Y., Alem, A. Z., Ayalew, H. G., Liyew, A. M., Tessema, Z. T., Tesema, G.

A. and Worku, M. G. (2022). “Socioeconomic inequality in barriers for accessing health care among married reproductive aged women in sub-Saharan African countries: a decomposition analysis,” BMC Women’s Health, vol. 22, no. 130, pp. 1 – 10. Available: HYPERLINK "https://doi.org/10.1186/s12905-022-01716-y" https://doi.org/10.1186/s12905-022-01716-y .

Alonzo, J. C., Nagra, V. P., Zschaebitz, J. V., Lake, D. E., Moorman, J. R. and Spaeder, M. C. (2018). “Heart rate ranges in premature neonates using high resolution physiologic data,” *Journal of Perinatol*, vol. 38, no. 9, pp. 1242 – 1245. Available: HYPERLINK "https://pmc.ncbi.nlm.nih.gov/articles/PMC6218802/pdf/nihms-994469.pdf" https://pmc.ncbi.nlm.nih.gov/articles/PMC6218802/pdf/nihms-994469.pdf .

Akant, P., Sengar, G., Zade, G., Ganvir, R. and Bharkade, N. (2017). “Design and development of patient monitoring system using Android application,” *IOP Publishing*, vol. 226, no. 1, pp. 012094.

Akpan, V. A. and Eyefia, S. A. (2021): “Autonomous Vehicle with Machine Vision and Integrated Sensor Suit Based on Internet-of-Things Technologies”, *International Journal of Electronics Engineering and Computer Science*, vol. 6, no. 3, pp. 18 – 30. Available [Online]: HYPERLINK "http://www.aiscience.org/journal/paperInfo/ijeecs?paperId=4702" http://www.aiscience.org/journal/paperInfo/ijeecs?paperId=4702 .

Akpan, V. A. and Olawale, F. V. (2024). “Development of fingerprint biometric authentication system for health information exchange”, *Journal of ICT Development, Applications and Research*, vol. 6, no. 2, pp. 1 – 16. Available [Online]: HYPERLINK "https://credence-publishing.com/journal/uploads/archive/202517374440115641481314.pdf" https://credence-publishing.com/journal/uploads/archive/202517374440115641481314.pdf . DOI: 10.47524/jictdar.v6i2.6.

Akpan, V. A., Adewumi, G. A. and Eyefia, S. A. (2019). The Development of an Enhanced Obstacle Detection System with Alarm Based on the Internet-of-Things”, *Journal of Advanced Research in Intelligent Systems and Robotics*, vol. 1, no. 2, pp. 12 – 29. Available [Online]: HYPERLINK "https://adrjournalshouse.com/index.php/Intelligence-Robotics-Sysytem/article/view/53" \t "_blank" https://adrjournalshouse.com/index.php/Intelligence-Robotics-Sysytem/article/view/53 .

Akpan, V. A., Eyefia, S. A. and Adewumi, G. M. (2021). “An IoT-Based Real-Time Embedded System for Gas-Smoke Detection with Automatic Electronic Alarm System”, *International Journal of Electronics Engineering and Computer Science*, vol. 6, no. 2, 7 – 17. Available [Online]: HYPERLINK "http://www.aiscience.org/journal/paperInfo/ijeecs?paperId=4686" http://www.aiscience.org/journal/paperInfo/ijeecs?paperId=4686 .

Amadi, H. O., Mokuolu, O. A., Adimora, G. N., Pam, S. D., Etawo, U. S., Ohadugha, C. O. and Adesiyun, O. O. (2007). “Digitally recycled incubators: better economic alternatives to modern systems in low-income countries,” *Annals of Tropical Paediatrics*, vol. 27, no. 3, pp. 207 – 214.

ANH (2025). “Arduino Nano Hardware,” Retrieved February 28th, 2025. Available [Online]: HYPERLINK "https://docs.arduino.cc/hardware/nano/" https://docs.arduino.cc/hardware/nano/ .

Antonucci, R., Porcella, A. and Fanos, V. (2009). “The infant incubator in the neonatal intensive care unit: unresolved issues and future developments,” *Journal of Perinatal Medicine*, vol. 37, no. 6, pp. 587 – 598. HYPERLINK "https://doi.org/10.1515/jpm.2009.109" https://doi.org/10.1515/jpm.2009.109

AQS (2025). “MQ2 Air Quality Sensor,”Retrieved February 28th, 2025. Available [Online]: HYPERLINK "https://www.elprocus.com/an-introduction-to-mq2-gas-sensor/" https://www.elprocus.com/an-introduction-to-mq2-gas-sensor/ .

Ashfaq, Z., Rafay, A., Mumtaz, R., Zaidi, S. M. H., Saleem, H., Zaidi, S. A. R. and Haque, A. (2022). “A review of enabling technologies for Internet of Medical Things (IoMT) Ecosystem,” *Ain Shams Engineering Journal*, vol. 13, no. 101660, pp. 1 – 19.

Athimoolam, S. and Karuppasamy, P. (2022). “Smart incubator for premature baby in an IoT Applications,” *Journal of Semiconductor Devices and Circuits*, vol. 9, no. 2, pp. 1 – 9.

Bouattoura, D., Villon, P. and Farges, G. (1998). “Dynamic programming approach for newborn’s incubator humidity control,” *IEEE Transactions on Biomedical Engineering*, vol. 45, no. 1, pp. 48–55. HYPERLINK "https://doi.org/10.1109/10.650351" https://doi.org/10.1109/10.650351 .

Boyd, H., Brand, M. C. and Hagan, J. (2017). “Care of 500 – 1500 gram premature infants in hybrid incubators,” *Advances in Neonatal Care*, vol. 17, no. 5, pp. 381 – 389. Available: DOI: HYPERLINK "https://doi.org/10.1097/anc.0000000000000422" \t "_blank" 10.1097/ANC.0000000000000422 .

Cone, T. E. (1981). “The first published report of an incubator for use in the care of the premature infant (1857),” *American Journal of Diseases of Children*, vol. 135, no. 7, pp. 658 – 660.

Dang, L. M., Piran, M. J., Han, D., Min, K. and Moon, H. (2019). “A Survey on Internet of Things and Cloud Computing for Healthcare,” *Electronics*, vol. 8, no. 7 (768), pp. 1 – 49. Available: HYPERLINK "https://doi.org/10.3390/electronics8070768" https://doi.org/10.3390/electronics8070768 .

Darniss, R., Nair, V. S., NB, S. S., and Devidas, A. R. (2022). "*An IoT based Vitals Monitoring System for Babies in Neonatal Intensive Care Unit*," In 2022 IEEE 10th Region 10 Humanitarian Technology Conference (R10-HTC), pp. 130 – 135.

Das, S., Chakraborty, P., Bora, R. and Chakraborty, P. (2023). "Sound levels and its effect on physiology of low birth weight newborns in a special care newborn unit – a prospective observational study," *Egyptian Pediatric Association Gazette*, vol. 71, no. 30, pp. 1 – 6. Available: HYPERLINK "https://doi.org/10.1186/s43054-023-00176-9.

9" https://doi.org/10.1186/s43054-023-00176-9.

DOLP (2025). "*Datex-Ohmeda Light Portable S/5*," Future Health Concepts, Retrieved February 28th, 2025. Available [Online]: HYPERLINK "https://www.futurehealthconcepts.com/patient-monitors/datex-ohmeda-light-portable-s-5.html" https://www.futurehealthconcepts.com/patient-monitors/datex-ohmeda-light-portable-s-5.html .

de Araújo Júnior, J. M., de Menezes Júnior, J. M. P., de Albuquerque, A. A. M., Almeida, O. D. M. and de Araújo, F. M. U. (2013). "Assessment and certification of neonatal incubator sensors through an inferential neural network," *Sensors*, vol. 13, no. 11, pp. 15613 – 15632.

Devaprasanth, S., Bhavadessh, D. and Dhanunjaya, G. (2022). "Wearable sensor with web server based incubator monitoring and control management system," *International Journal of Research Publications and Reviews*, vol. 3, no. 5, pp. 501 – 506.

Dike, U. C. and Jackson, V. M. (2024). "Telemedicine integration with cloud-based IoT: A literature review approach," *World Journal of Advanced Research and Reviews*, vol. 24, no. 2, pp. 723 – 731. Available: DOI: HYPERLINK "https://doi.org/10.30574/wjarr.2024.24.2.3355" https://doi.org/10.30574/wjarr.2024.24.2.3355 .

DTH (2025). "DHT11 Temperature and Humidity Sensor,"Retrieved February 28th, 2025. Available [Online]: HYPERLINK "https://components101.com/sensors/dht11-temperature-sensor" https://components101.com/sensors/dht11-temperature-sensor .

El-Aziz, R. M. A. and Taloba, A. I. (2021). "Real Time Monitoring and Control of Neonatal Incubator using IOT," *International Journal of Grid and Distributed Computing*, vol. 14, no. 1, pp. 2117 – 2127.

Elhoseny, M., Thilakarathne, N. N., Alghamdi, M. I., Mahendran, R. K., Gardezi, A. A., Weerasinghe, H. and Welhenge, A. (2021). "Security and privacy issues in medical internet of things: overview, countermeasures, challenges and future directions," *Sustainability*, vol. 13, no. 11645, pp. 1 – 31. Available: HYPERLINK "https://doi.org/10.3390/su132111645" https://doi.org/10.3390/su132111645 .

Fahmi, F., Shalannanda, W., Zakia, I. and Sutanto, E. (2020). "Design of an IoT-based smart incubator that listens to the baby," *In IOP Conference Series: Materials Science and Engineering*, vol. 1003, No. 012153, pp. 1 – 8. Available: HYPERLINK "https://iopscience.iop.org/article/10.1088/1757-899X/1003/1/012153/pdf" https://iopscience.iop.org/article/10.1088/1757-899X/1003/1/012153/pdf .

Firmansyah, R., Widodo, A., Romadhon, A. D., Hudha, M. S., Saputra, P. P. S. and Lestari, N. A. (2019). "The prototype of infant incubator monitoring system based on the Internet of Things using NodeMCU ESP8266," *Journal of Physics: Conference Series*, vol. 1171, no. 012015, pp. 1 – 9. Available: HYPERLINK "https://doi.org/10.1088/1742-6596/1171/1/012015" https://doi.org/10.1088/1742-6596/1171/1/012015 .

Gaber, M. M., Aneiba, A., Basurra, S., Batty, O., Elmisery, A. M., Kovalchuk, Y. and Rehman, M. H. U. (2019). "Internet of Things and data mining: From applications to techniques and systems," *Wiley Interdisciplinary Reviews, Data Mining and Knowledge Discovery*, vol. 9, no. 3, e1292.

Gat, R., Kachko, E., Kloog, I., Erez, O., Yitshak-Sade, M., Novack, V. and Lena N. L. (2021). "Differences in environmental factors contributing to preterm labor and PPROM – Population based study," *Environmental Research*, vol. 196, no. 110894, pp. 1 – 7. Available: HYPERLINK "https://doi.org/10.1016/j.envres.2021.110894" https://doi.org/10.1016/j.envres.2021.110894 .

Ha, S. and Mendola, P. (2017). "Invited Commentary: Ambient Environment and the Risk of Preterm Birth," *American Journal of Epidemiology*, vol. 185, no. 4, pp. 259 – 261. Available: HYPERLINK "https://doi.org/10.1093/aje/kww138" https://doi.org/10.1093/aje/kww138 .

Henderson, A. and McDonagh, D. (2017). "The preemie pod: A wearable incubator designed for premature infants to engage in Kangaroo care," *An International Journal for All Aspects of Design*, vol. 20, no. 1, pp. S4791 – S4793. Available: HYPERLINK "https://doi.org/10.1080/14606925.2017.1352994" https://doi.org/10.1080/14606925.2017.1352994 .

Henslee, J. A., Schechtman, V. L., lee, M. Y. and harper, R. M. (1997). "Developmental patterns of heart rate and variability in prematurely-born infants with apnea of prematurity," *Early Human Development*, vol. 47, no. 1, pp. 35 – 50. Available: HYPERLINK "https://doi.org/10.1016/S0378-3782(96)01767-7" \t "_blank" \o "Persistent link using digital object identifier" https://doi.org/10.1016/S0378-3782(96)01767-7 .

Hess, J. H. (1922). "Premature and congenitally diseased infants," Lea and Febiger, Philadelphia, U.S.A. pp. 1 – 415.

Ho, C., Robinson, A., Miller, D. and Davis, M. (2005). "Overview of Sensors and Needs for Environmental Monitoring," *Sensors*, vol. 5, no. 1, pp. 4 – 37. Available: HYPERLINK "https://doi.org/10.3390/s5010004" https://doi.org/10.3390/s5010004 .

HPS (2025). "SEN-11574 Heart Pulse Sensor," Retrieved February 28th, 2025. Available [Online]: HYPERLINK "https://www.microscale.net/products/heart-pulse-sensor-sen-11574?srsltid=AfmBOoo6K_jJqZVVGn-d7QTo1clI26s7F_ep8jGpnWqDgI6s8f761aNA" https://www.microscale.net/products/heart-pulse-sensor-sen-11574?srsltid=AfmBOoo6K_jJqZVVGn-d7QTo1clI26s7F_ep8jGpnWqDgI6s8f761aNA .

Huang, T. and Sun, L. (2015). "Design and implementation of the infant incubator intelligent control system based on internet of things," *The Open Automation and Control Systems Journal*, vol. 7, no. 1, pp. 2223 – 2229.

Indhuja, G., Abinaya, R., Sneka, S., Lakshmi, M. and Karpagam, R. (2023) "Development of hybrid power baby incubator," *International Journal of Research in Engineering and Science*, vol. 11, no. 5, pp. 582 – 584.

Iranpak, S., Shahbahrami, A. and Shakeri, H. (2021). "Remote patient monitoring and classifying using the internet of things platform combined with cloud computing," *Journal of Big Data*, vol. 8, no. 120, pp. 1 – 22. Available: HYPERLINK "https://doi.org/10.1186/s40537-021-00507-w" https://doi.org/10.1186/s40537-021-00507-w .

Islam, S. R., Kwak, D., Kabir, M. H., Hossain, M., & Kwak, K. S. (2015). "The internet of things for health care: a comprehensive survey," *IEEE Access*, vol. 3, pp. 678 – 708.

Islam, T., Hassan, R., Romy, S. R., Dellal D. and Bin, T. R. A. (2023). "Enhancing Medication Adherence with IoT Technology," *European Journal of Electrical Engineering and Computer Science*, vol. 7, no. 5, pp. 7 – 13. Available: HYPERLINK "https://doi.org/10.24018/ejece.2023.7.5.557" 10.24018/ejece.2023.7.5.557 .

Issa, B. A. and Thabit, Q. Q. (2021). "Review in IoT for Healthcare in Our Life," *Iraqi Journal of Electrical and Electronics Engineering*, vol. 18, pp. 9 – 20.

James, M. (2021). "*Clinical Guideline: Management of a baby requiring humidity Version 2.0 Humidity for infants < 30 weeks gestation*", East of England Neonatal Benchmarking Group, Cambridge University Hospital, United Kingdom, pp. 1 – 9. Available: HYPERLINK "https://www.eoeneonatalpccsicnetwork.nhs.uk/wp-content/uploads/2021/10/Humidity-Guideline.pdf" https://www.eoeneonatalpccsicnetwork.nhs.uk/wp-content/uploads/2021/10/Humidity-Guideline.pdf .

Jegadeesan, S., Dhamodaran, M., Azees, M. and Shanmugapriya, S. S. (2019). "Computationally efficient mutual authentication protocol for remote infant incubator monitoring system," *Healthcare Technology Letters*, vol. 6, no. 4, pp. 92 – 97.

Kalilani, M., Lai, N. S. and Abdulla, R. (2021). "IOT based neonatal incubator for the developing world and conflict zones," *Journal of Applied Technology and Innovation*, vol. 5, no. 4, pp. 44 – 50.

Kapadia, V. S., Kawakami, M. D., Strand, M. L., Hurst, C. P., Spencer, A., Schmölzer, G. M., Rabi, Y Wyllie, J., Weiner, G., Helen G. Liley, H. G. and Wyckoff, M. H. (2024). "Fast and accurate newborn heart rate monitoring at birth: A systematic review," *Resuscitation Plus*, vol. 19, no. 100668, pp. 1 – 21. Available: HYPERLINK "https://doi.org/10.1016/j.resplu.2024.100668" \t "_blank" \o "Persistent link using digital object identifier" https://doi.org/10.1016/j.resplu.2024.100668 .

Keikhosrokiani, P. (2021). "IoT for enhanced decision-making in medical information systems: A systematic review," Enhanced Telemedicine and e-Health. Studies in Fuzziness and Soft Computing, vol. 410, pp. 119 – 140.

Khawas, C., and Shah, P. (2018). Application of firebase in android app development-a study. *International Journal of Computer Applications*, *179*(46), 49-53.

Kshirsgar, P., More, V., Hendre, V., Chippalkatti, P. and Paliwal, K. (2020). "IOT based baby incubator for clinic," *In ICCCE 2019:Proceedings of the 2nd International Conference on Communications and Cyber Physical Engineering*, pp. 349 – 355. Springer Singapore.

KYHS (2025). KY-039 Heartbeat Sensor, The Geek Publications. Retrieved February 15th, 2025. Available [Online]: HYPERLINK "https://www.thegeekpub.com/wiki/sensor-wiki-ky-039-heartbeat-sensor/" https://www.thegeekpub.com/wiki/sensor-wiki-ky-039-heartbeat-sensor/ .

KYS (2025). "KY-014-039 Finger Heartbeat Sensor,"Retrieved February 28th, 2025. Available [Online]: HYPERLINK "https://www.microscale.net/products/finger-heartbeat-sensor?srsltid=AfmBOopijXT_HS1rEzggaHZXyfbQiGJnI0_9DGOWTmPDF4eyDikjpnGa" https://www.microscale.net/products/finger-heartbeat-sensor?srsltid=AfmBOopijXT_HS1rEzggaHZXyfbQiGJnI0_9DGOWTmPDF4eyDikjpnGa .

Laurie, G. (2021). "Preterm infant incubator humidity levels: A systematic review," *Advances in Neonatal Care*, vol. 24, no. 4, pp. 297 – 307. Available: DOI: 10.1097/ANC.0000000000000791.

Lin, L. Z., Chen, J. H., Yu, Y. J. and Dong, G. H. (2023). "Ambient air pollution and infant health: a narrative review," *eBioMedicine*, vol. 93, no. 104609, pp. 1 – 9. Available: HYPERLINK "https://doi.org/10.1016/j.ebiom.2023.104609" \t "_blank" \o "Persistent link using digital object identifier" https://doi.org/10.1016/j.ebiom.2023.104609 .

Linu, J., Emmanuel, B. P., Sandesh, M., Muhammed, A. P., Sankaranarayan, C. M. and Vismaya, R. (2024). "Smart incubator using IoT," *International Journal of Progressive Research in Science and Engineering*, vol. 5, no. 5, pp. 25 – 30.

Madakam, S., Ramaswamy, R. and Tripathi, S. (2015). "Internet of Things (IoT): A Literature Review," *Journal of Computer and Communications*, vol. 3, no. 5, pp. 164 – 173. Available: HYPERLINK "https://doi.org/10.4236/jcc.2015.35021" https://doi.org/10.4236/jcc.2015.35021 .

Mageshkumar, G., Kasthuri, N., Tamilselvan, K., Suthagar, S. and Sharmila, A. (2020). "Design of industrial data monitoring device using IoT Through MODBUS Protocol," *Internal Journal of Science and Technology Research*, vol. 9, pp. 1392 – 1396.

Mageshkumar, S. S., and Tamilsevan, K. S. (2022). "Baby Incubator Monitoring System using Global System for Mobile Technology," *Jurnal Kejuruteraan*, vol. 34, no. 5, pp. 899 – 904. Available: HYPERLINK "https://doi.org/10.17576/jkukm-2022-34(5)-17" https://doi.org/10.17576/jkukm-2022-34(5)-17 .

Martinez, A. W., Cáceres, F. D. and Martinez, K. F. (2023). "IoT Based Infant Incubator Monitoring System," 2023 IEEE Latin American Electron Devices Conference, 3rd – 5th July, 2023, Puebla, Mexico. Pp. 1 – 5. Available: DOI: HYPERLINK "https://doi.org/10.1109/LAEDC58183.2023.10209121" \t "_blank" 10.1109/LAEDC58183.2023.10209121 .

MathWorks (2025). *MATLAB & Simulink® 2025*, The MathWorks Inc, Natick, U.S.A. Available: HYPERLINK "http://www.mathworks.com" www.mathworks.com .

Maynard, K. R., Causey, L., Kawaza, K., Dube, Q., Lufesi, N., Maria Oden, Z., Richards-Kortum, R. R. and Molyneux, E. M. (2015). "New technologies for essential newborn care in under-resourced areas: what is needed and how to deliver it," *Paediatrics and International Child Health*, vol. 35, no. 3, pp. 192 – 205. Available: HYPERLINK "https://doi.org/10.1179/2046905515y.0000000034" https://doi.org/10.1179/2046905515y.0000000034 .

MQ2 (2025). Gas Sensor Module. Indiamart.com. Retrieved February 28th, 2025, Available [Online]: HYPERLINK "https://www.indiamart.com/proddetail/mq-2-gas-sensor-module-19274547712.html" https://www.indiamart.com/proddetail/mq-2-gas-sensor-module-19274547712.html .

Mutanu, L., Gupta, K., and Gohil, J. (2022). "Leveraging IoT solutions for enhanced health information exchange," *Technology in Society*, vol. 68, pp. 101882.

NCH (2025). "*Physical Exam of the Newborn*," Nationwide Children Hospital, 700 Chldren Drive, Columbus, OH 43205, United States of America. Available [Online]: HYPERLINK "https://www.nationwidechildrens.org/conditions/health-library/physical-exam-of-the-newborn" https://www.nationwidechildrens.org/conditions/health-library/physical-exam-of-the-newborn .

NMCU (2025). "NodeMCU ESP8266 hardware," Retrieved February 28th, 2025. Available [Online]: HYPERLINK "https://www.make-it.ca/nodemcu-details-specifications/" https://www.make-it.ca/nodemcu-details-specifications/ .

Nodejs (2025): "Run JavaScripts Anywhere". Available [Online]: HYPERLINK "https://nodejs.org/en" https://nodejs.org/en . Accessed 25th of January, 2025.

Ohuma E., Moller, A. B. and Bradley E. (2020) "National, regional, and worldwide estimates of preterm birth in 2020, with trends from 2010: a systematic analysis," *Lancet*, vol. 402, no. 10409, pp.1261 – 1271. DOI:10.1016/S0140-6736(23)00878-4.

OSSH (2025) Ondo State Specialist Hospital, Hospital Road, Akure 340283, Ondo State, Nigeria.

Perin, J., Mulick, A., Yeung, D., Villavicencio, F., Lopez, G., Strong, K.L., Prieto-Merino, D., Cousens, S., Black, R.E. and Liu, L. (2022) "Global, regional, and national causes of under-5 mortality in 2000-19: An updated systematic analysis with implications for the Sustainable Development Goals," *Lancet Child Adolescent Health*, vol. 6, pp. 106 – 115. Available: HYPERLINK "https://www.thelancet.com/action/showPdf?pii=S2352-4642%2821%2900311-4" https://www.thelancet.com/action/showPdf?pii=S2352-4642%2821%2900311-4 .

PJSF (2025): "The progessive JavaScript Framework". Available [Online]: HYPERLINK "https://vuejs.org/" https://vuejs.org/ . Accessed 25th of January, 2025.

Raharja, N. M. and Sugiyarta, I. S. (2022). "Current Trends in Incubator Control for Premature Infants with Artificial Intelligence Based on Fuzzy Logic Control: Systematic Literature Review", *Journal of Robotics and Control*, vol. 3, no. 6, pp. 863 – 877. Available: DOI: 10.18196/jrc.v3i6.13341.

Rajalakshmi, A., Sunitha, K.A. and Venkataraman, R. (2019). A Survey on Neonatal Incubator Monitoring System. *Journal of Physics: Conference Series*, vol. 1362, no. 1, pp. 012128. doi:https://doi.org/10.1088/1742-6596/1362/1/012128.

Rayan, R. A., Tsagkaris, C. and Iryna, R. B. (2021). "The Internet of Things for Healthcare: Applications, Selected Cases and Challenges," *IoT in Healthcare and Ambient Assisted Living*, pp. 1 – 15. Available: HYPERLINK "https://doi.org/10.1007/978-981-15-9897-5_1" https://doi.org/10.1007/978-981-15-9897-5_1 .

Redcliff Labs (2025) "*Difference Between Heart Rate and Pulse Rate!*," H55 Electronic City, H Block, Sector 63, Nodia, Uttar, Pradesh 201301, India. Available [Online]: HYPERLINK "https://redcliffelabs.com/myhealth/heart/difference-between-heart-rate-and-pulse-rate/" https://redcliffelabs.com/myhealth/heart/difference-between-heart-rate-and-pulse-rate/ .

Ritz, B., Wilhelm, M., Hoggatt, K. J. and Ghosh, J. K. C. (2007). "Ambient Air Pollution and Preterm Birth in the Environment and Pregnancy Outcomes Study at the University of California, Los Angeles", *American Journal of Epidemiology*, vol. 166, no. 9, pp. 1045 – 1052. Available: HYPERLINK "https://doi.org/10.1093/aje/kwm181" https://doi.org/10.1093/aje/kwm181 .

Sahoo, S., Champaty, B., Pal, K., Ray, S. S. and Tibarewala, D. N. (2014). "Wireless transmission of alarm signals from baby incubators to neonatal nursing station*," In 2014 IEEE First International Conference on Automation, Control, Energy and Systems (ACES)*, 1st – 2nd February, 2014, Adisaptagram, India, pp. 1 – 5. Available**:** DOI: HYPERLINK "https://doi.org/10.1109/ACES.2014.6808003" \t "_blank" 10.1109/ACES.2014.6808003 .

Sasu, D. D. (2024). "Mortality rate of infants under one year old in Nigeria as of 2023 by gender," Published September 30th, 2024. Retrieved on February 28th, 2025. Available [Online]: HYPERLINK "https://www.statista.com/statistics/1203486/infant-mortality-rate-in-nigeria-by-gender/" https://www.statista.com/statistics/1203486/infant-mortality-rate-in-nigeria-by-gender/ .

Shahzad, K. and Oelmann, B. (2014, August). "A comparative study of in-sensor processing vs. raw data transmission using ZigBee, BLE and Wi-Fi for data intensive monitoring applications," In 2014 IEEE 11th International Symposium on Wireless Communications Systems (ISWCS), Barcelona, Spain, 2014, pp. 519-524, DOI: 10.1109/ISWCS.2014.6933409.

SLSM (2025). "LM393 Sound Level Sensor,"Retrieved February 28th, 2025. Available [Online]: HYPERLINK "https://circuitmall.ng/product/lm393-microphone-sound-sensor-module/" https://circuitmall.ng/product/lm393-microphone-sound-sensor-module/ .

Sunyaev, A. (2020). "Cloud Computing," In: *Internet Computing*, pp. 195–236. Springer. Available: HYPERLINK "https://doi.org/10.1007/978-3-030-34957-8_7" https://doi.org/10.1007/978-3-030-34957-8_7 .

Surantha, N., Atmaja, P., David, A. and Wicaksono, M. (2021). "A Review of Wearable Internet-of-Things Device for Healthcare," *Procedia Computer Science*, vol. 179, no. 2021, pp. 936 – 943. Available: DOI: 10.1016/j.procs.2021.01.083.

Suresh, P., Daniel, J. V., Parthasarathy, V. and Aswathy, R. H. (2014). "A state of the art review on the Internet of Things (IoT) history, technology and fields of deployment," *In 2014 IEEE International conference on science engineering and management research (ICSEMR)*, Chennai, India, 2014, pp. 1-8, doi: 10.1109/ICSEMR.2014.7043637.

Tarouco, L. M. R., Bertholdo, L. M., Granville, L. Z., Arbiza, L. M. R., Carbone, F., Marotta, M. and De Santanna, J. J. C. (2012). "Internet of Things in healthcare: Interoperability and security issues," *In 2012 IEEE international conference on communications (ICC)*, Ottawa, ON, Canada, 2012, pp. 6121-6125, doi: 10.1109/ICC.2012.6364830.

Thilakarathne, N. N. and Kagita, M. K. (2020). "The Role of the Internet of Things in Health Care: A Systematic and Comprehensive Study," *International Journal of Engineering and Management Research*, vol. 10, no. 4, pp. 145 – 159. Available: HYPERLINK "https://doi.org/10.31033/ijemr.10.4.22" https://doi.org/10.31033/ijemr.10.4.22 .

Tisa, T.A., Nisha, Z.A., and Kiber, M.A. (2013), "Design of an enhanced temperature control system for neonatal incubator," *Bangladesh Journal of Medical Physics*, vol.5, no.1, pp. 53 – 61.

Usman, A. K., Wolka, E., Tadesse, Y., Tariku, A., Yeshidinber, A., Teklu, A. M., Senturia, K., Gezahegn, W. and Litch, J. A. (2019). "Health system readiness to support facilities for care of preterm, low birth weight, and sick newborns in Ethiopia: a qualitative assessment," *BMC Health Services Research*, vol. 19, no. 1., pp. 1 – 16. Available: HYPERLINK "https://doi.org/10.1186/s12913-019-4672-2" https://doi.org/10.1186/s12913-019-4672-2 .

Vermesan, O. and Friess, P. (2014). "*Internet of things applications - From research and innovation to market deployment*," 1st Edition, pp. 1 – 364. Taylor & Francis, New York, U.S.A.

Vermesan, O., Friess, P., Guillemin, P., Sundmaeker, H., Eisenhauer, M., Moessner, K. and Baldini, G. (2022). "*Internet of things strategic research and innovation agenda. In Internet of Things Applications - From Research and Innovation to Market Deployment*," pp. 1 - 373. River Publishers Series in Communication, Aalborg, Denmark.

WHO (2021) "*WHO Global Air Quality Guidelines*," pp. 1 – 300. Available: HYPERLINK "https://iris.who.int/bitstream/handle/10665/345329/9789240034228-eng.pdf" https://iris.who.int/bitstream/handle/10665/345329/9789240034228-eng.pdf .

Witti, M. and Konstantas, D. (2018). "A secure and privacy-preserving internet of things framework for smart city," In Proceedings of the 6th International Conference on Information Technology: IoT and Smart City, 29th – 31st

December, 2018, Hong Kong, China, pp. 145 – 150. Available: HYPERLINK "https://dl.acm.org/doi/10.1145/3301551.3301607" https://dl.acm.org/doi/10.1145/3301551.3301607 .

Yuehong, Y. I. N., Zeng, Y., Chen, X. and Fan, Y. (2016). "The internet of things in healthcare: An overview," *Journal of Industrial Information Integration,* vol. 1, pp. 3 – 13.

Zaylaa, A. J., Rashid, M., Shaib, M. and Majzoub, I. E. (2018). "A Handy Preterm Infant Incubator for Providing Intensive Care: Simulation, 3D Printed Prototype, and Evaluation," *Journal of Healthcare Engineering*, Vol. 2018, no. 8937985, pp. 1 – 14. Available: HYPERLINK "https://doi.org/10.1155/2018/8937985" https://doi.org/10.1155/2018/8937985 .

Zhou, I., Makhdoom, I., Shariati, N., Raza, M. A., Keshavarz, R., Lipman, J. and Jamalipour, A. (2021). "Internet of things 2.0: Concepts, applications, and future directions," *IEEE Access*, vol. 9, pp. 70961 – 71012.

Zhou, W., Jia, Y., Yao, Y., Zhu, L., Guan, L., Mao, Y., Liu, P. and Zhang, Y. (2019). "Discovering and understanding the security hazards in the interactions between iot devices, mobile apps, and clouds on smart home platforms," In Proceedings of the 28th USENIX Security Symposium, 14th – 16th August, 2019, Santa Clara, CA, U.S.A., pp. 1133 – 1150. Available: HYPERLINK "https://par.nsf.gov/servlets/purl/10181334" https://par.nsf.gov/servlets/purl/10181334 .

Zivaljevic, J., Jovandaric, M. Z., Babic, S. and Raus, M. (2024). "Complications of Preterm Birth – The Importance of Care for the Outcome: A Narrative Review," *Medicina*, vol. 60, no. 6, pp. 1 - 10. Available: HYPERLINK "https://doi.org/10.3390/medicina60061014" https://doi.org/10.3390/medicina60061014 .

APPENDIX 1: Software for the implementation of the designed and constructed proposed system for the real-time monitoring of neonatal incubator using IoT technology

```
#include <Arduino.h>
#if defined(ESP32)
#include <WiFi.h>
#elif defined(ESP8266)
#include <ESP8266WiFi.h>
#include <WifiUdp.h>
#include <IPAddress.h>
#include <NTPClient.h>
#endif
#include <LiquidCrystal.h>
#include "DHT.h"
#include <Firebase_ESP_Client.h>
#include "addons/TokenHelper.h"
#include "addons/RTDBHelper.h"
#include <map>
#include <string>

// Replace with your Wi-Fi network credentials
const char* ssid = "vivo 1902";
const char* password = "Charleee";

// Insert Firebase project API Key
#define API_KEY "AIzaSyBHVuPQW2feHmjGgHnzcxS_j7jj1aHSxeo"
// Insert RTDB URLefine the RTDB URL */
#define DATABASE_URL "https://babymonitor-charles-default-rtdb.firebaseio.com/"

/* 4. Define the user Email and password that already registerd or added in your project */
#define USER_EMAIL "charles@gmail.com"
#define USER_PASSWORD "charles@gmail.com"

constint RS = 14, EN = 2, d4 = 0, d5 = 4, d6 = 5, d7 = 16;
LiquidCrystallcd(RS, EN, d4, d5, d6, d7);

#define DHTTYPE DHT11
#definedht_dpin 10
DHT dht(dht_dpin, DHTTYPE);
#definegasPin 15
#define sound 12
#define BPM 13
#define PULSE A0
intgasVal;

//Define Firebase Data object
FirebaseDatafbdo;
FirebaseAuthauth;
FirebaseConfigconfig;
FirebaseJsonjson;

// Define pin for the relay
constint relay = 0;
intrelay_status = 0;
const long utcOffsetInSeconds = 3600;

WiFiUDPudp;
NTPClienttimeClient(udp, "pool.ntp.org", utcOffsetInSeconds);
void setup() {
// put your setup code here, to run once:
Serial.begin(9600);
pinMode(relay, OUTPUT);

// Connect to Wi-Fi
WiFi.begin(ssid, password);
Serial.printf("\nConnecting to %s", ssid);

while (WiFi.status() != WL_CONNECTED) {
delay(1000);
Serial.printf("...connecting to ", ssid);
  }
Serial.printf("\nConnected to %s\n", ssid);

// Print ESP8266 IP address
IPAddresslocalIP = WiFi.localIP();
Serial.printf("IP address: %s\n", localIP.toString().c_str());

//..................FIREBASE DATABASE...............
Serial.printf("Firebase Client v%s\n\n", FIREBASE_CLIENT_VERSION);
  /* Assign the api key (required) */
config.api_key = API_KEY;
  /* Assign the user sign in credentials */
auth.user.email = USER_EMAIL;
auth.user.password = USER_PASSWORD;
  /* Assign the RTDB URL (required) */
config.database_url = DATABASE_URL;
  /* Assign the callback function for the long running token generation task */
config.token_status_callback = tokenStatusCallback; //see addons/TokenHelper.h
Firebase.begin(&config, &auth);

  /* Sign up */
  if (Firebase.signUp(&config, &auth, "", "")) {
Serial.println("ok");
    //  signupOK = true;
  }

  //Comment or pass false value when WiFi reconnection will control by your code or third party library
Firebase.reconnectWiFi(true);
Firebase.setDoubleDigits(5);
timeClient.begin();
}
void loop() {
float pulse;
int sum = 0;
intsoundL;
  float h = dht.readHumidity();
  float t = dht.readTemperature();

  for (inti = 0; i< 20; i++)
    sum += analogRead(BPM);
pulse = ((sum / 20.00) / (12.85));
soundL = digitalRead(sound);
gasVal = digitalRead(gasPin);
  String fsound = (soundL == LOW) ? " PLEASE CHECK SOUND" : "SOUND IS OKAY";
String fgas = (gasVal == LOW) ? "POOR AIR" : "AIR QUALITY OKAY";

// Write the JSON object to Firebase
// Define the user ID
const String userID = "123";

  if (Firebase.ready()) {

// Define the data to be set in the Firebase Realtime Database
std::map<String, String> data = {
{ "temperature", String(t) },
{ "humidity", String(h) },
{ "airquality", String(fgas) },
{ "sound", String(fsound) },
{ "pulse", String(pulse) },
{ "bpm", String(pulse) }
    };

 // Loop through the data and set each value in the Firebase Realtime Database
    for (const auto& [key, value] : data) {
Firebase.RTDB.setString(&fbdo, "users/" + userID + "/" + key, value);
    }

 // Printing values to the Serial Monitor
Serial.printf("\n** SENSORS REPORT *************\n");
Serial.printf("humidity : %.2f%%\n", h);
Serial.printf("temperature : %.2f°C\n", t);
Serial.printf("sound : %s\n", fsound.c_str());
Serial.printf("gas: %s\n", fgas.c_str());
Serial.printf("pulse : %.2fBPM\n", pulse);
Serial.printf("BPM : %.2fBPM\n", pulse);
Serial.printf("***************\n");

// Printing values to the LCD
lcd.clear();
lcd.setCursor(0, 0);
lcd.printf("humid = %.2f%%\n", h);
lcd.setCursor(0, 1);
lcd.printf("temp = %.2f%°C\n", t);
delay(2000);
lcd.clear();
lcd.setCursor(0, 0);
lcd.println(fgas);
delay(2000);
lcd.clear();
lcd.setCursor(0, 0);
lcd.println(fsound);
delay(2000);
lcd.clear();
lcd.setCursor(0, 1);
lcd.printf(" BPM IS: %.2fBPM\n", pulse);
delay(1000);
  } else {
 // Handle the case where Firebase is not ready
Serial.println("Firebase is not ready.");
  }
}
```