ORIGINAL ARTICLE

Enhancing Neonatal Care Through an IoT-Based Monitoring System for Infant Incubators

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ABSTRACT

Introduction: Neonatal Intensive Care Units (NICUs) often face challenges such as understaffing and high workloads, which can compromise the quality of newborn care. Conventional monitoring systems lack mobile integration and real-time alert capabilities, limiting the responsiveness of healthcare providers. This study introduces a proof-of-concept prototype system aimed at improving neonatal monitoring through an IoT-based solution. **Materials and Methods**: The system integrates an ESP32 microcontroller with a DHT11 sensor for temperature and humidity monitoring, an AD8232 ECG sensor for heart rate detection, and an infrared (IR) sensor for infant positioning. Real-time data visualization and alert notifications are facilitated via the Blynk mobile application. The system was developed using the Rapid Application Development (RAD) methodology, encompassing requirements analysis, system design, additive manufacturing, and testing and validation phases. **Results:** Experimental results demonstrate that heart rate readings from the prototype exhibit minimal percent error when compared to the Samsung Galaxy Watch 5 (-1.32% to 1.82%) and a mobile heart rate app (-2.56% to 2.17%). Temperature readings showed percent error ranges of -5.94% to 5.29% against an incubator display and -3.29% to 4.33% compared to the FLUKE Baby Incubator Tester. Humidity readings displayed higher percent errors, ranging from -13.69% to -7.92%, indicating the need for improved sensor calibration. The system successfully detected positional changes of a baby manikin and issued alerts within 10 seconds. **Conclusion:** Overall, the prototype offers a practical and cost-effective approach to enhancing neonatal care through continuous monitoring and mobile integration. Further improvements are recommended to address humidity sensing limitations.
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Keywords: Baby positioning, Heart rate monitoring, Infant incubator, IoT, Temperature monitoring.

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INTRODUCTION

Ensuring adequate resources and medical personnel to meet the needs of infants and monitor their health is essential, particularly within Malaysia's healthcare system. Gupta R. et al. (1) conducted a hospital-based prospective observational study that offers valuable insights into the factors influencing neonatal outcomes, with the aim of improving survival rates among these vulnerable infants. The admission of premature neonates to Neonatal Intensive Care Units (NICUs) due to low birth weight highlights the critical importance of effective neonatal care (Mittal H. et al., 2; Martнnez et al., 3). Mittal H. et al. (2) emphasize the role of infant incubators in maintaining controlled environmental conditions vital for newborns. Asmidar N. et al. (4) further note that, to provide an optimal environment, incubators should maintain an internal ambient temperature between 36°C and 37°C, with a relative humidity level of 70% to 75%. Technological and medical advancements have contributed significantly to the evolution of neonatal care (5), but challenges remain. High workloads and limited personnel can hinder continuous monitoring, potentially compromising the quality of care delivered to neonates (6).

Several recent studies have proposed IoT-based solutions for infant incubators. For instance, Khotimah et al. (7) developed a Bluetooth-enabled incubator for temperature monitoring; Asmidar et al. (4) designed a portable incubator for rural clinics; and Ahmed et al. (8) proposed a smart incubator using Arduino Uno. Other notable innovations include an AI-integrated incubator capable of interpreting infant cries (9) and a cloud-based incubator system for remote access to infant data

(10). These efforts demonstrate progress, yet also reveal limitations such as reliance on basic microcontrollers, lack of integrated health monitoring, or absence of real-time alerts which affect efficiency and scalability.

Despite these efforts, the literature lacks sufficient discussion on the operational issues encountered in implementing such systems, especially regarding integration, accuracy, and reliability in real clinical settings. Moreover, there is a gap in literature explicitly justifying the need for further research, particularly in the Malaysian context, where rural healthcare facilities face greater technological constraints (Rwechungura et al., 11).

This project addresses these limitations by developing a comprehensive IoT-based monitoring proof-of-concept prototype system for infant incubators, aimed at enhancing neonatal care while optimizing cost and functionality. In response to this need, the objectives of the research are threefold: First, to develop a device prototype capable of monitoring environmental parameters, baby positioning, and the heart rate of an infant within the incubator. Second, to implement Internet of Things (IoT) functionality that enables real-time data transmission to a smartphone via Wi-Fi using the ESP32 microcontroller. Finally, the study aims to test and validate the functionality and reliability of the system in monitoring heart rate, temperature, humidity, and baby positioning.

Sheikh S.A. et al. (12) highlight that the exclusive use of the ESP32 chip in their system design eliminates the need for additional processors, thereby simplifying the hardware architecture. According to Sheikh S.A. et al. (12), the ESP32 is specifically engineered for mobile, wearable, and IoT applications, offering integrated proprietary software that is optimized for low power consumption. Furthermore, Sheikh S.A. et al. (12) note that the ESP32 supports advanced features such as fine-grained clock gating, multiple power modes, and dynamic power scaling, which contribute to its efficiency and suitability for energy-constrained environments. As demonstrated by Maier, Sharp, and Vagapov (13), the ESP32 offers a practical, high-performance solution for IoT applications. As highlighted by Jayakumar S. et al. (14), Selvanayakam A. et al. (15), and Usha Rani S. et al. (16), the applications of the Internet of Things (IoT) are broad and diverse, spanning various sectors such as healthcare, transportation, agriculture, manufacturing, smart homes, and smart cities. In the healthcare domain, IoT devices play a significant role by enabling the continuous tracking of patients' vital signs and transmitting this data to healthcare providers in real time (Abarna S.S. et al., 17; Malays J Med Health Sci., 2024 [18]; Senillosa M.B. et al., 19). This capability facilitates remote monitoring and allows for timely medical interventions (Abarna S.S. et al., 17; Malays J Med Health Sci., 2024 [18]; Senillosa M.B. et al., 19).

This project contributes to this growing trend by using the ESP32 microcontroller to interface with sensors that monitor temperature, humidity, heart rate, and baby positioning. The proof-of-concept prototype system integrates the DHT11 for environmental parameters, the AD8232 for ECG-based heart rate measurement, and an IR sensor for position detection. Data is displayed in real time via the Blynk mobile app, and alerts are issued if the infant moves too close to the incubator wall, helping ensure optimal air circulation and safety.

Notably, unlike previous studies, this project employs the AD8232 ECG sensor in place of a conventional pulse oximeter due to its improved reliability and accuracy, aligning with Prasad and Kavanashree’s (20) findings. Furthermore, the integration of the Blynk app with ESP32 microcontrollers for infant care applications has not been widely explored in past research, making this a novel contribution.

In summary, while prior work has laid a foundation for IoT applications in neonatal care, gaps in integration, scalability, and clinical deployment persist. This study aims to bridge these gaps by introducing a cost-effective, IoT-enabled monitoring solution tailored to the needs of Malaysian NICUs, especially in resource-constrained settings.

MATERIALS AND METHODS

Rapid application development

Dennis et al. (21) provides a comprehensive comparison between Agile and Waterfall methodologies, outlining their key differences and applications in project management. Rapid Application Development (RAD) methodology was adopted for the development of the IoT-based monitoring system proof-of-concept prototype for neonatal care, as illustrated in Fig. 1. RAD is suitable for small-scale projects with well-defined requirements, enabling iterative development, rapid prototyping, and continuous testing (21). The RAD process in this study comprised four main phases: requirement analysis, system design and additive manufacturing, testing and validation, and deployment. This methodology allowed for flexible iterations to improve functionality and address integration issues throughout the development lifecycle.

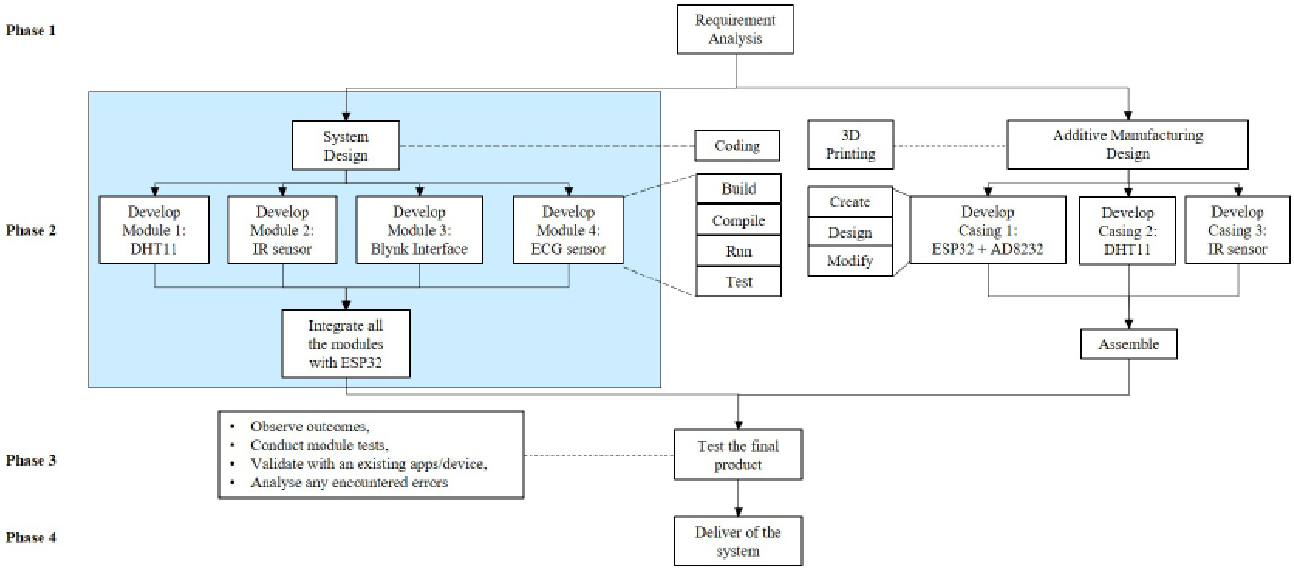


Fig 1: Rapid Application Development (RAD) model of this system.

Requirement analysis

The initial phase involved a detailed requirement analysis to determine the essential hardware and software components suitable for the infant incubator environment. The selection of components was guided by reviewing existing incubator specifications, studying operational parameters within neonatal intensive care units (NICUs), and informal consultations with healthcare staff. This analysis helped to identify the need for continuous monitoring of critical parameters such as temperature, humidity, heart rate, and infant positioning. Accordingly, the DHT11 sensor was chosen for ambient temperature and humidity monitoring due to its reliability and compact form factor. The IR sensor was selected to detect the infant's position within the incubator, while the AD8232 ECG sensor was employed to measure heart rate through bioelectrical signals. All components were selected for their compatibility with the ESP32 microcontroller, which was central to the system. Software tools included the Arduino IDE for embedded system programming and the Blynk IoT platform for wireless data visualization on a mobile device.

System design and additive manufacturing design

The second phase addressed the design of the overall system and the fabrication of the proof-of-concept prototype casing using additive manufacturing. The hardware circuit was built around the ESP32 microcontroller, with wired connections to the DHT11, IR, and AD8232 sensors. The ESP32 was selected for its low power consumption and integrated Wi-Fi capability, enabling real-time wireless communication with the Blynk platform. The embedded software was developed using the Arduino IDE in C/C++, programming the microcontroller to collect sensor data, process it, and transmit it to the Blynk cloud service. The logic flow included initializing sensor inputs, reading and filtering data, and sending data packets to the Blynk dashboard for visualization.

Parallel to this, the physical design of the proof-of-concept prototype casing was completed using Tinkercad, and the components were 3D printed using PLA material. Individual casings were designed for each sensor module and for the combined ESP32-AD8232 unit. These casings ensured a secure fit, sensor alignment, and accessibility for testing and demonstration purposes. The compact and modular structure facilitated integration into an incubator-like test environment, enhancing usability and replicability.

Testing and validation

The third phase involved rigorous testing and validation to ensure sensor accuracy and system reliability. The proof-of-concept prototype was USB-powered through a standard power bank, ensuring portability and real-time functionality. Sensor performance was benchmarked against reference devices and systems.

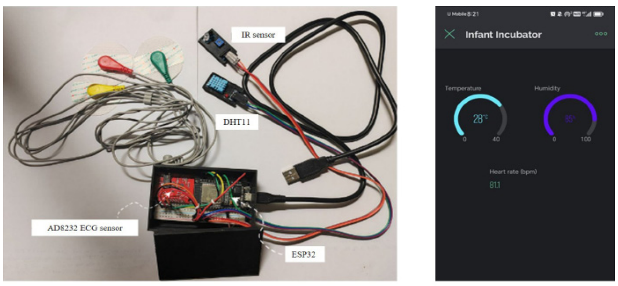
Heart Rate Measurement: The heart rate sensor testing involved 10 healthy adult participants aged between 21 to 50 years. Electrodes were placed on each subject, followed by a 5–10-minute rest period. Subjects then wore the Samsung Galaxy Watch 5 and used a Play Store heart rate app. Simultaneous reading from the proof-of-concept prototype, smartwatch, and app were recorded across 10 trials. This study was approved by the Universiti Teknologi Malaysia Research Ethics Committee (Approval No.: UTMREC-2025-124), and all participants provided informed consent. Two commercially available devices were used as benchmarks for the heart rate measurement comparison: the Samsung Galaxy Watch 5, registered under Malaysia's Medical Device Authority (MDAR), and a heart rate monitoring app available from the Google Play Store. The Galaxy Watch 5 was selected for its clinical reliability and regulatory recognition, while the heart rate app represents the type of widely accessible, low-cost solution used in non-clinical settings. This dual comparison allows for assessing the prototype's accuracy against both certified and widely-used reference systems.

Temperature Measurement: The internal ambient temperature testing compared the prototype's readings with those from the faculty's infant incubator and the FLUKE Infant Incubator Tester. After a 10-minute stabilization period, temperature readings were recorded every 5 minutes from all three sources. The data validated the prototype's consistency and accuracy under controlled conditions. A total of 30 datasets were obtained.

Humidity Measurement: Humidity testing followed a similar setup to the temperature validation. The FLUKE Infant Incubator Tester was used as the reference device, with the prototype placed inside the incubator alongside it. Humidity values were recorded at 10-minute intervals to ensure reliable performance comparisons under the same environmental conditions. In total, 15 dataset values were obtained.

Baby Positioning Detection: To evaluate the accuracy and responsiveness of the baby positioning detection system, a total of 20 trials were conducted using a neonatal manikin. The trials were evenly divided between two distinct position zones within the incubator: Safe Zone (from the centre to half the incubator length) and Danger Zone (within one-quarter length of the incubator wall). The term "Safe Zone" refers to a place receiving proper air circulation from all directions within the incubator. Each zone was tested 10 times to assess consistency and detection reliability.

System Integration and Communication: Sensor data was transmitted from the ESP32 to the Blynk platform via a Wi-Fi connection. Although the system was fully integrated, the Arduino IDE remained necessary for serial data transmission and debugging during prototype validation. This indicates that while the system is functional, it has not yet been transitioned to a standalone deployment phase. This continued dependence on the Arduino IDE is justified as part of iterative testing and optimization before final deployment.



(a) (b)

Figure 2: (a) Infant incubator proof-of-concept prototype system. (b) Blynk app interface showing real-time data.

RESULTS

Project design

The prototype device, as illustrated in Fig. 2(a), integrates input sensors DHT11, IR sensor, and AD8232 with the system processor ESP32. This setup connects to output devices, including a mobile application interface that displays temperature, humidity, and heart rate values, along with notification features, as shown in Fig. 2(b).

Table I (a): Error of difference in heart rate measurement between two existing devices/apps and the prototype device. (b): Error of difference in humidity measurement between an existing device and the prototype device.

(a) Heart rate measurement

Prototype Device	Samsung Galaxy Watch 5		Heart rate app (Play Store)	
Measured Heart rate (bpm)	Heart rate (bpm)	*Error of Difference* (bpm)	Heart rate (bpm)	*Error of Difference* (bpm)
90	90	0	89	1
112	110	2	112	0
84	84	0	85	-1
76	77	-1	78	-2
81	82	-1	81	0
76	75	1	76	0
83	83	0	84	-1
94	93	1	92	2
106	106	0	107	-1
75	76	-1	75	0

Error values (in beats per minute, bpm) represent the difference between measurements taken by the prototype device and two existing devices: Samsung Galaxy Watch 5 and the Heart Rate App (Play Store). The error of difference (bpm) is calculated as: Measured heart rate value (bpm) -Existing app/devices heart rate value (bpm).

(b) Humidity measurement

Infant Prototype Device	FLUKE Infant Incubator Tester	
Recorded Humidity (%)	Humidity (%)	*Difference*(%)
48	55	-7
41	47.1	-6.1
48	54.9	-6.9
50	57	-7
45	50.2	-5.2
39	43.7	-4.7
36	39.1	-3.1
34	38.1	-4.1
38	42.5	-4.5
41	46.1	-5.1
42	48	-6
46	53.3	-7.3
48	55	-7
44	49	-5
41	47.5	- 6.5

Error values (in percentage) represent the difference between measurements taken by the prototype device and the FLUKE infant incubator tester. The error of difference (%) is calculated as: Measured humidity value (%) – Existing device's humidity value (%).

Heart rate measurement

Table I (a) presents the differences in heart rate readings between the proof-of-concept prototype and the two reference devices. The error range was between -1 and +2 bpm for both of the Samsung Galaxy Watch 5, and for the Play Store app. The average error difference was calculated to be 0.7 bpm and 0.8 bpm, respectively. In terms of percentage error, the Galaxy Watch 5 ranged from -1.32% to 1.82%, while the Play Store app ranged from -2.56% to 2.17%. These values fall well within the accepted clinical tolerance of ±5% (22), suggesting that the prototype device is capable of providing heart rate readings with accuracy comparable to both a medically certified device and a reliable commercial app.

Temperature measurement

Temperature readings from the proof-of-concept prototype were compared against two standards: the infant incubator's built-in display and the FLUKE Infant Incubator Tester, a recognized reference instrument. As shown in Table II, the prototype's error difference compared to the infant incubator ranged from -1.6°C to +1.7°C, while the comparison with the FLUKE tester ranged from -0.82°C to +1.48°C. The corresponding average errors were 0.64°C and 0.58°C, respectively. Percentage error for the FLUKE comparison ranged from -3.29% to 4.33%, staying within the acceptable ±5% margin, whereas the incubator display readings ranged from -5.94% to 5.29%, marginally exceeding the limit in some cases. This implies that while the prototype provides temperature measurements generally within acceptable range, periodic recalibration may be required for optimal performance in clinical applications.

Table II: Error of difference in temperature measurement between two existing devices and the prototype device

Prototype Device	Infant Incubator		FLUKE Infant Incubator Tester	
Recorded Temp (℃)	Temp (℃)	*Error of Difference* (℃)	Temp (℃)	*Error of Difference* (℃)
29.3	30.5	-1.2	29.05	0.25
31.8	31.2	0.6	31.18	0.62
31.95	32.4	-0.45	31.35	0.6
30.8	30.5	0.3	29.45	1.35
29.8	30.1	-0.3	28.96	0.84
28.9	29.5	-0.6	28.6	0.3
28.8	28.6	0.2	28.58	0.22
27.1	27.4	-0.3	26.92	0.18
24.1	24.8	-0.7	24.92	-0.82
30.8	31.6	-0.8	31.17	-0.37
29.8	30.2	-0.4	30.22	-0.42
27.1	28.5	-1.4	27.67	-0.57
26.7	28.2	-1.5	26.57	0.13
25.3	26.9	-1.6	25.92	-0.62
24.8	24.9	-0.1	24.49	0.31

continue

Table II: Error of difference in temperature measurement between two existing devices and the prototype device (cont.)

Prototype Device	Infant Incubator		FLUKE Infant Incubator Tester	
Recorded Temp (℃)	Temp (℃)	*Error of Difference* (℃)	Temp (℃)	*Error of Difference* (℃)
25.3	25.4	-0.1	25.21	0.09
26.2	27.2	-1.0	26.65	-0.45
25.8	26.8	-1.0	25.87	-0.07
33.8	32.1	1.7	32.88	0.92
35.6	35	0.6	34.12	1.48
24.1	25.1	-1.0	24.89	-0.79
24.5	25.4	-0.9	25.01	-0.51
25.75	26.9	-1.15	26.09	-0.34
27.7	28.5	-0.8	27.73	-0.03
28.5	28.7	-0.2	28.07	0.43
30.8	31	-0.2	30.1	0.7
31.3	31.1	0.2	30.22	1.08
31.8	31.9	0.1	30.96	0.84
32.3	32.3	0	31.12	1.18
33.3	33.3	0	33.02	0.28

Error values (in degrees Celsius, °C) represent the difference between measurements taken by the prototype device and two existing devices: the infant incubator and the FLUKE infant incubator tester. The error of difference (°C) is calculated as: Measured temperature value (°C) – Existing devices' temperature value (°C).

Humidity measurement

The humidity readings were evaluated against the FLUKE Infant Incubator Tester, as detailed in Table I (b). The error of difference ranged between -7.3% and -3.1%, with an average error of 5.7% and percentage error spanning from -13.69% to -7.92%. These results indicate that the proof-of-concept prototype's humidity sensor readings do not meet the ±5% accuracy requirement. The deviation suggests that the current sensor calibration or sensor selection needs refinement to achieve clinical-grade performance. Future system iterations may consider using higher-precision humidity sensors or implementing software-level correction algorithms.

Baby positioning

The system employs multi-point IR sensors to determine the manikin's proximity to the incubator wall. As per Fig. 3(a), when placed in the Safe Zone, the system correctly identified the position in all 10 trials, with no alerts triggered, confirming adequate airflow conditions. In contrast as per Fig. 3(b), when the manikin was positioned in the Danger Zone, the system successfully detected the proximity in all 10 trials, triggering alerts and sending real-time notifications via the Blynk mobile application to inform medical personnel, as illustrated in Fig. 3(c).

These results confirm that the IR-based positioning system effectively distinguishes between safe and potentially

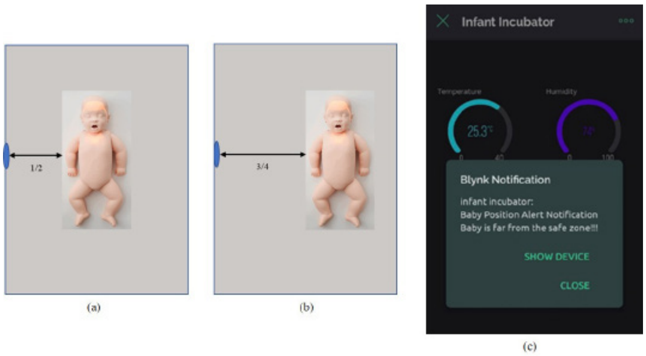


Figure 3: (a) Manikin in "Safe Zone" inside incubator. (b) Manikin near incubator wall. (c) Blynk app showing alert after 10 seconds.

hazardous positions within the incubator. The consistent detection accuracy across all trials supports its suitability for enhancing neonatal safety by preventing airflow obstruction due to improper positioning.

DISCUSSION

The proof-of-concept prototype device developed in this study exhibited strong performance across key neonatal monitoring parameters: heart rate, temperature, humidity, and baby positioning; offering a comprehensive and cost-effective solution for real-time neonatal care monitoring.

Performance Overview

Heart rate accuracy was validated against the Samsung Galaxy Watch 5 and a Play Store app, with percentage errors ranging from -1.32% to 1.82% and -2.56% to 2.17%, respectively within the clinical threshold of ±5%. The use of the AD8232 sensor for ECG-based heart rate monitoring is reliable.

Temperature readings were highly reliable, particularly when compared to the FLUKE Infant Incubator Tester (-3.29% to 4.33%), aligning with clinical expectations. While the comparison with the incubator display showed slightly higher errors (-5.94% to 5.29%), the results remain largely acceptable. Humidity measurements, however, fell outside the acceptable range, indicating that further calibration is necessary.

In baby positioning, the IR sensor accurately distinguished between safe and unsafe zones during 20 trials across three positions. Real-time alerts were delivered via the Blynk mobile app, improving caregiver responsiveness.

Comparison with Prior Studies

This project addresses significant limitations found in past research and commercial systems. Unlike Khotimah et al. (7) who relied on short-range Bluetooth, this system uses Wi-Fi via ESP32, which supports lower latency, greater range, and more stable real-time communication. Unlike Asmidar et al. (4) and Ahmed et al. (8), who focused narrowly on temperature control without remote or real-time monitoring, this system integrates multiple physiological and environmental parameters into one cohesive IoT-based platform. Furthermore, while Fahmi et al. (9) and Sivamani et al. (10) addressed real-time auditory monitoring and remote storage respectively, they lacked multi-sensor integration and immediate alert mechanisms offered here.

Table III: Comparative Summary

Study	Focus	Sensors Used	Connectivity	Real-Time Alert	Limitations Addressed in This Work
Khotimah et al. (7)	Temp monitoring using Bluetooth	Temp	Bluetooth	No	Low-range, lacks heart rate & alerts
Asmidar et al. (4)	Transportable incubator with temp control	Temp	None	No	No IoT, no multi-sensor support
Ahmed et al. (8)	Low-cost incubator with basic monitoring	Temp	None	No	No remote access, limited sensors
Fahmi et al. (9)	Cry recognition for infant incubator monitoring using IoT & ML	Sound sensor (microphone)	Wi-Fi	No	Added cry-based monitoring via Machine Learning; no vitals, no movement detection, no safety zoning
Sivamani et al. (10)	Smart incubator with data storage	Temp, humidity	Wi-Fi	No	No heart rate, no alert notifications
Martínez et al. (3)	IoT-based neonatal incubator monitoring	Temp, humidity, vitals	Wi-Fi	No	No heart rate or movement detection; no real-time alerts; limited validation; no comparison with other systems
Rwechungura et al. (11)	Low-cost neonatal care monitoring system	Temp, humidity, heart rate, oxygen sensor, UV sensor	Wi-Fi	Yes	No motion detection or zoning alerts; limited real-time interface and multi-parameter fusion; validation confined to temperature and humidity in controlled settings.
This study	Multi-sensor IoT neonatal monitoring system	Temp, humidity, ECG, IR	Wi-Fi (ESP 32)	Yes	All limitations addressed; integrates vitals & environment, real-time alerts, mobile access, all parameters validated, low-cost single-chip design

Additionally, Martínez et al. (3) emphasized that low birth weight significantly increases the need for effective neonatal care, reinforcing the importance of real-time, multi-parameter monitoring solutions like the one developed in this study. Their findings underscore the clinical relevance of this work, especially in resource-limited environments where low-cost and scalable monitoring is critical.

Similarly, Rwechungura et al. (11) proposed an IoT-based smart incubator for environmental monitoring, but their approach did not include vital sign tracking or real-time alert mechanisms. The present study addresses these limitations by incorporating ECG-based heart rate monitoring, movement detection, and instant alerts, thereby offering a more holistic solution to neonatal care challenges. A comparative summary is presented in Table III.

CONCLUSION

The proof-of-concept prototype device demonstrated strong potential for neonatal care by providing accurate heart rate and temperature monitoring, with percentage errors well within acceptable clinical limits when compared to standard devices like the Samsung Galaxy Watch 5, a mobile heart rate app, and the FLUKE Infant Incubator Tester. Although humidity measurements showed higher percentage errors ranging from -13.69% to -7.92%, likely due to environmental influences or sensor limitations, the system successfully detected unsafe baby positioning using IR sensors, ensuring enhanced safety. To further improve the system's performance particularly in humidity monitoring future work should explore the integration of higher-precision humidity sensors (e.g., SHT31 or HIH6100), implement real-time auto-calibration algorithms, and conduct extended field testing under varying environmental conditions to account for factors like airflow, temperature gradients, and incubator material properties. Incorporating advanced sensor calibration methods and improving shielding against external environmental interference could also enhance overall accuracy and reliability in long-term clinical deployment.

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