IOT based neonatal incubator for the developing world and conflict zones

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***Abstract*—The aim of this research is to develop a low-cost neonatal incubator unit with IOT functionality for use in the developing world and conflict zones which currently see 99% of all neonatal deaths due to the financial constraints in the regions preventing the adoption of conventional incubator units. The proposed system incorporated the development of a functional neonatal incubator unit incorporating various biometric sensors for assessment of the infant's condition through the use of an IOT application developed using the Blynk IOT platform. The performance of the developed proposed system is evaluated by testing the system's ability to create a desired microclimate within the incubator enclosure as well as assessing the accuracy of the biometric sensors used. It is observed that the incubator system is capable of creating the desired microclimate. The biometric sensors used are observed to produce comparable results to measurements taken simultaneously on medical grade equivalents. Tests conducted show the system achieves an extreme case humidity of 95% within a 5-minute period and autonomously maintain a humidity within the 90-95% range. The integration of the monitoring system with the low-cost incubator, and the numerous biometric sensors used produced a proposed system not presently available as determined by the literature reviewed.**

***Keywords*— *Neonatal incubator, national health service, IOT integration, body temperature, infant's health*.**

I. INTRODUCTION

Neonatal death is defined as the deaths among live born infants within 28 days of birth [1]. Of the roughly 6.3 million global under-five child deaths occurring annually, nearly half the deaths at 44% occur within the neonatal period [2]. As an intervention, infants born with conditions that may increase their probability of death, such as low birth weight and preterm birth are placed in the Neonatal Intensive Care Unit (NICU) of which various medical instruments are used to assist the newborns through this critical period, the main instrument being the neonatal incubator [3]. A neonatal incubator is a special piece of medical apparatus that provides a controlled microclimate which facilitates the sustenance of newborns during the neonatal period [4]. Neonatal incubators have proven vital in reducing the neonatal mortality rate globally, however, their benefits are felt more in resource rich, developed nations resulting in roughly 99% of neonatal deaths occurring in low- and middle-income countries [2].

The developing world sees nearly 20 million premature/low-birth weight infants born annually, of which 4 million die within the neonatal period [3]. The high neonatal mortality rate in this region is seen to stem from two key factors. Firstly, due to the economical constraints many developing countries incur, high priced medical instruments such as neonatal incubators are often drastically insufficient in number compared to the number of infants born in requirement of them, resulting in an increase in the number of neonatal deaths. Secondly, the shortage in medical personnel in many hospitals in these regions is also seen to contribute to the staggeringly high neonatal mortality rate. A shortage in qualified medical personnel is seen to be associated to increased deaths, with the British National Health Service (NHS) recording an estimated 28,000 deaths as a result of this shortage annually [5].

Another area of the modern world seeing an increased number of neonatal deaths are the world's conflict zones. Due to the conflict in these regions, adequate health care is difficult to access. Adding to this, exposure to armed conflict has been found to increase the probability of complication during pregnancy resulting in an increased number of low birth weight & premature births [6]. Without access to adequate incubation, an alarming number of these infants are susceptible to dying within the neonatal period. Like the developing world, many medical installations in conflict zones are often understaffed, further adding to the preventable neonatal deaths in these regions. In the recent years, advancement of technology has led to an increase in research and development of IoT devices [7-14].

This research aims to develop a low-cost neonatal incubator with IOT integration to facilitate diagnosis and treatment of the infants during the neonatal period, to help reduce the currently staggeringly high neonatal mortality rate in low- & middle- income countries and conflict zones. The proposed system will read key biometric information such as body temperature, pulse rate, blood oxygen levels & respiration rate to mention a few as well as transmit the readings for analysis via an algorithm to determine the condition of the infant. This information, readily available to the medical personnel via a web or mobile application will allow for a systematic evaluation of the infants, overall improving their diagnosis and treatment and ultimately reducing the neonatal mortality rate in the regions.

The high cost of commercial hardware puts the life-saving technologies out of reach of infants in economically constrained areas, thus the development of a low cost variant with similar capabilities to the higher priced commercial incubators will be highly beneficial in reducing the neonatal mortality rate in these regions, which make up 99% of the global annual neonatal deaths. The understaffed conditions in these regions is also seen to contribute to the staggeringly high

neonatal mortality rate and as such, an advanced monitoring system capable of monitoring multiple infants at once is ideal in assisting the limited medical personnel in diagnosis and treatment of the infants.

To achieve this, specific parameters relating to the infant's health must be known such as the optimal/desired temperature, humidity, heart rate and blood oxygen saturation readings of the infants during the neonatal period as well as the range of readings that would be considered abnormal.

The next problem involves the hardware (sensors) reading the necessary biometric data, ensuring their accuracy in medical applications and compatibility in use with infants, while maintaining a low cost.

The processing of the biometric data for analysis of the health of the infants through fuzzy computation is an area of significance in aiding the medical personnel evaluate the condition of the infants. The optimal to abnormal range of readings can be used as indicators to determine the infant's health through a processing algorithm of which numerous types exist, varying in use case, response time, etc. It is then of high importance to determine which processing algorithms are best suited for application in determining the overall health of a patient based on numerous biometric inputs.

Data from the processing system must be transferred to the database for storage and to allow for the remote monitoring of the infants. The processing hardware used, and the database created must be compatible in all necessary aspects to allow for this. Secondly, as medical data is being shared between the subsystems, and stored on the database, it is imperative that the mode of transmission between the processing system and database itself be highly secure. It is thus of importance to determine which database systems are compatible with the selected hardware and have a high security record, crucial in the handling of medical data.

After reading the biometric data, the analysis of infant's condition and transmission of data to the database, this information must then be illustrated on a platform in real time for examination by the medical personnel, facilitating the diagnosis and treatment of the infants in the understaffed conditions. Various existing platforms can illustrate the necessary information as required by the medical personnel, however, compatibility of said system with the database mentioned prior as well as the overall cost of utilising the platform must be taken into consideration. The research problem identified is to determine the most cost-effective platform compatible with the database to use in illustrating the received medical data.

Therefore, the aim of this research is the development of a low-cost neonatal incubator capable of producing a suitable environment necessary for the survival of infants in the neonatal period while using IOT technology to facilitate the diagnosis and treatment of the infants in understaffed conditions.

[15] proposed the development of a temperature measurement system to implement within incubators due to the importance of temperature variable during premature/low birth weight infant incubation. The methodology of the system involves the use of LM35 precision temperature sensor, an analogue to digital converter (ADC), an Advanced Virtual RISC (AVR) Microcontroller and LCD Display. The system works by reading the temperature via the LM35 temperature sensor whose output is fed into the input of the ADC which converts voltage reading from the LM35 to a quantifiable digital output. This digital output is input into the AVR Microcontroller which is programmed to send the result to the LCD screen for observation. The infant incubator monitoring system was tested on a dummy unit on which the system functioned successfully.

[16] proposed the development of a low-cost incubator providing the necessary environment for infants in the neonatal period. The methodology applied in this research involves the use of DS18B20 and LM35 temperature sensors, DHT11 and SHT11 humidity sensors, a heating element, water bath, potentiometers and an Arduino Mega 2560 microcontroller all integrated together forming a PID control Circuit. The system works by laying the infant on a mattress placed under a canopy creating an enclosed environment. The desired temperature and humidity are set via potentiometer. The temperature is adjusted by the heating element situated under the mattress. The results of testing the system show a noticeable change of temperature with respect to time, with a quick system response time attributed to the use of the DS18B20 sensor.

[17] proposed the design and development of an Arduino based humidity and temperature control infant incubator with special attention given to the comfort of the infant because of the pain and soreness infants are subjected to in the initial weeks of incubation due to the invasive methods of treatment such as the placement and removal of sensors for checking critical parameters. The system composed of respiration, humidity, temperature and pressure sensors for monitoring their respective parameters. The system was tested and various parameters such as temperature, humidity, respiration and pressure were monitored on the LCD screen. These values were transferred to the parents and doctors via the GSM module.

[18] proposed the research and development of a 3D printed prototype of a handheld preterm incubator providing indispensable intensive care at a low cost for low income countries to lower the neonatal mortality rate. The methodology of the system involved the Max 30100 oximeter and heart rate sensor, a digital thermometer, cartridge heater, chemical wax, a 3D printed enclosure as well as the Atmega 328 and Arduino micro microcontrollers. The system functioned by placing the infant in the enclosure, immediately of which the infants heart rate, temperature and SpO2 (blood oxygen saturation) are monitored by the microcontrollers. According to the authors, the collection of more data from the MAX 30100 oximetry sensor can be done in order to improve the oximetry readings in future iterations, as well as the use of Peltier cells (semiconductor thermoelectric component) instead of a heating element. Finally, the provision of a webserver and web application for remote monitoring/telehealth of the infants and research purposes was stated as an additional innovation to be added.

[19] proposed the development of an inexpensive and reliable device that monitors the temperature and air humidity of neonatal incubators and notifies medical personnel via a web or mobile application when a critical variation is detected. According to the authors, low birth weight newborns are in requirement of thermoneutral environments controlling variable such as temperature and air humidity to avoid developmental impairments and lower the mortality rate and

the integration of said systems with IOT technology can enhance the management of the technology associated with health services. The methodology used involved the use of the ESP8266 NodeMCU microcontroller, DHT22 digital temperature and humidity sensor, and red & yellow LEDs. The NodeMCU microcontroller was programmed for a desired humidity of 75% and temperature range between 34 and 35°C. The system was tested in a functioning Vision 2286 incubator and was seen to offer high monitoring precision and successfully triggered the LEDs if the monitored values deviated from the desired range

II. SYSTEM IMPLEMENTATION

For the physical incubator enclosure, the material of choice remained poly (methyl methacrylate), also known as acrylic, however, for the successful use and assembly of the prototype system, the 3D computer aided design created prior must be improved upon, detailing the different individual components that'll make up the enclosure, incorporating the specific type of acrylic used (referring to the colour, opacity and thickness), the fabrication methods used and how the individual components will come together to for the enclosure.

Firstly, the thickness chosen for the acrylic glass used for the enclosure is 5mm. The overall system was divided into two sections, namely; the lower "Base", made of white opaque acrylic and design to house and conceal the system components required to operate the system as well as the upper "Canopy", made of transparent acrylic, allowing for the visual examination of the infant. Each component was designed with protrusions and indentations to fit into adjacent components and improve the overall structural integrity of the enclosure. Fig.1 illustrates how all components come together in the form of an exploded view. The canopy section of the enclosure consists of a series of bends on adjacent sides, which cannot be created with the CAM laser cutting manufacturing process to be used as it is 2D based and cuts predesigned shapes from flat sheets of material, of which is the form acrylic takes upon manufacture. This required translation of the curved design pieces into equivalent flat designs which can bent into the desired shapes. This was achieved using the Solidworks sheet metal design tool which allows for the simulated bending of flat design files. Based on this a flat design file was created and bent into the desired design profile shown in the exploded view in Fig 1.

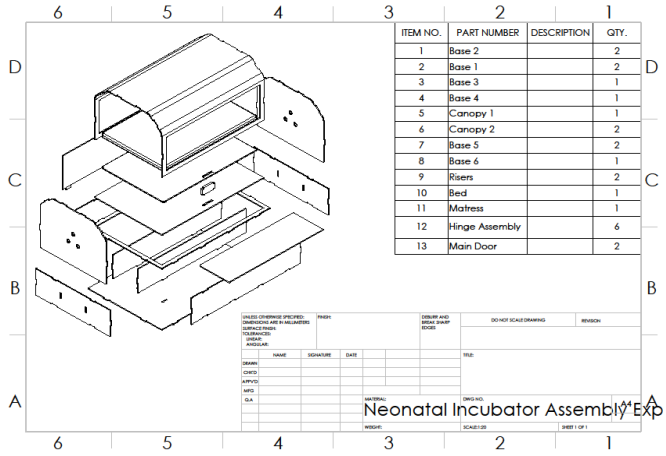

Fig. 1. CAD design exploded view

Secondly, using the components designed, a final assembly was formed detailing the components used and their quantities in the bill of materials. Based on this additional assemblies were created with each component laid face down and adjacent to the other, in a layout best suited for the efficient laser cutting of the acrylic and to minimise the quantity of waste material produced. Appendix J illustrates the assemblies made, exported in the Drawing Exchange Format (DXF), which is the 2D vector file format required to operate the laser cutting machinery used.

Finally, the designed shapes were subsequently made using the laser cutting process, allowing for the commencement of the construction phase of the incubator unit. The individual components were pieced together based on the layout set in the design file, allowing for the quick assembly of the enclosure. Additional adhesive was used to hold the components together and provide further strength. The flat canopy piece and canopy doors were bent into their desired shapes with the aid of a heat gun used to soften the material at the various bent points, manipulated into shape and cooled. Various openings were drilled into the Base components to allow for the passing of wires within the different compartments of the Base and for the passing of sensor cables from the base compartment to the canopy above. The assembly of the incubator is illustrated in Fig 2. during the integration of the electrical and electronic hardware components into the enclosure.

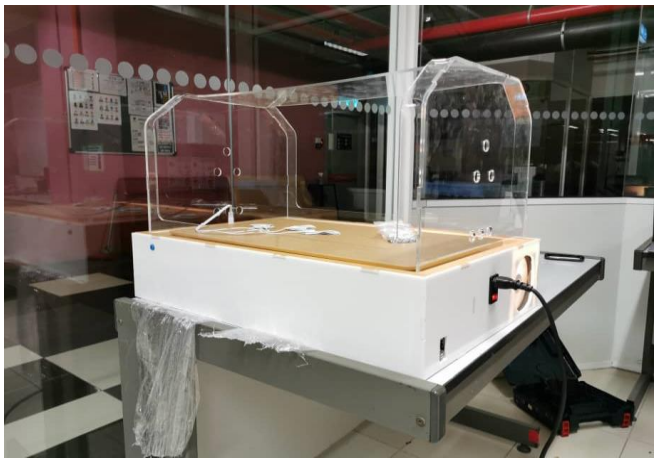

Fig. 2. Partially assembled incubator system

Additionally, further components were designed and created using the extrusion manufacturing processes of 3D printing to form external components used to house system hardware components, namely, the system LCD display cover and fan cover.

III. WORKING PRINCIPLE

The proposed system works according to the flowchart illustrated in Fig 3. The system is initialized the fan in the system is run at medium speed. A connection is established with the online server after which data is retrieved from the 4 sensors in the system. Body temperature readings are taken from the DS18B20 sensor. The readings are assessed to see if they meet the set threshold value. If the body temperature falls below that given value, a higher duty cycle PWM signal is sent to the fan increasing its speed and the relay switch is triggered providing power to the nichrome heating element thus raising the ambient temperature within the incubator. If the

temperature happens to be above the threshold value, the fan speed is set to medium and the relay switch is triggered open, cutting power to the heating element. An identical procedure is done with the ambient temperature in the enclosure of which is measured via the DHT22 sensor. The ambient temperature readings obtained are processed via the Arduino microcontroller and if the ambient temperature falls below the programmed threshold ambient temperature value, a higher duty cycle PWM signal is sent to the fan increasing its speed and the relay switch is triggered providing power to the nichrome heating element thus raising the ambient temperature within the incubator. If the temperature happens to be above the threshold value, the fan speed is set to medium and the relay switch is triggered open, cutting power to the heating element. Humidity control within the enclosure also occurs in an identical manner to the ambient temperature control. The humidity value detected by the DHT22 sensor is assessed much like the ambient and body temperature. If the humidity falls below a se threshold value, the nebulizer of which is placed in a shallow reservoir of water is provided power by the triggering of the normally open relay switch. Activation of the nebulizer provides and the raising of the fan speed increases the humidity within the enclosure, raising the humidity above the threshold value where the microcontroller triggers the relay switch open, cutting power to the nebulizer and setting the fan speed to medium.

The MAX30102 pulse oximeter upon initialization reads the patients heart rate and blood oxygen saturation. No actuation occurs based on the detected readings as they are required simply for medical observation and assessment of the infants condition. The AD8232 ECG sensor is the final sensor and upon initialization detects the infant's heart's electrical activity and illustrates this in the form of an ECG waveform. The analog waveform detected by the waveform is transmitted to the microcontroller. Just as with the MAX30102 pulse oximeter, no actuation occurs based on this signal as it is simply meant for observation and assessment of the infant.

All detected signals are illustrated in the systems LCD display and are transmitted to the Blynk IOT application. On the Blynk IOT application, the homepage illustrates multiple incubators detailing the body temperature of the infant in each incubator. Clicking on a specific incubator from the home page will provide a detailed breakdown of all measured variables from the incubator, allowing medical personnel to assess the infants condition based on the real-time biometric data given.

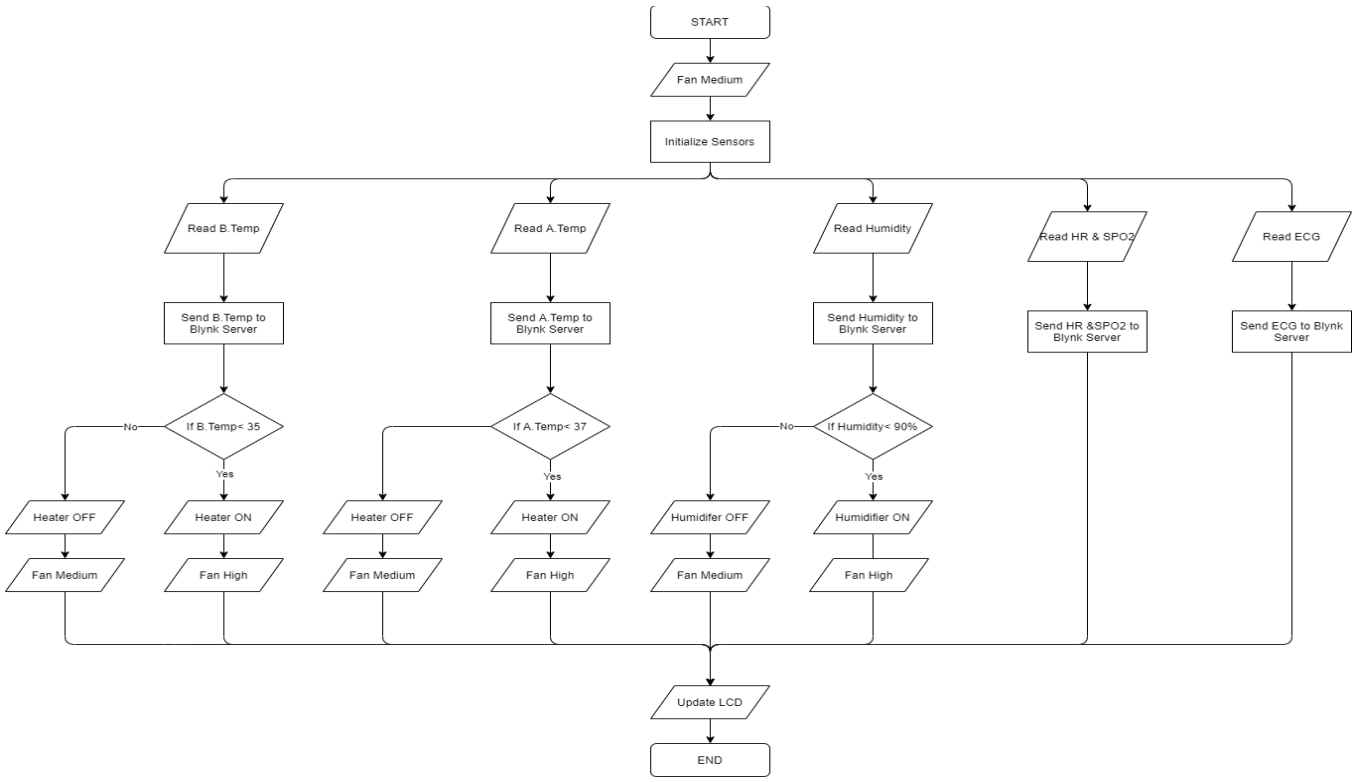

Fig. 3. Overall system flowchart

IV. HARDWARE RESULTS

Upon completion of the construction and programming of the proposed IOT Neonatal incubator the system was initialised and performance assessed. The system was capable of detecting signals from all sensors as well as adjusting the fan speed and actuating the nebulizer and heater via the dual channel relay switch. The sensory data detected was indicated on the 20x4 LCD display. When connected to a internet ready network via the sensory data was illustrated in real time on the Blynk application. Fig 4. illustrates the NICU Monitoring application homepage detailing the body temperature of 4 different incubator systems. Patient 1 of which indicates a body temperature of 35.94 degrees Celsius is the incubator system that has been developed, whereas patients 0, 2 and 4 are arbitrary units represented by NodeMCU boards to show the system's ability to display multiple incubator units on

through a single application accomplishing the 3rd objective highlighted for the project. Clicking on a specific patient number on the applications homepage opens a tab for the specific incubator unit illustrating all sensory data as shown in Fig 4. As per design, the tab for patient 1 indicates the incubators ambient temperature and humidity, as well as the patient's body temperature, heart rate, blood oxygen saturation and ECG waveform.

Fig. 4. Blynk home page and Patient 1 page

V. TESTING

A) *Humidity Control Test*

The ability for the developed incubator system to create a high humidity environment is crucial for the maintaining the neonates body temperature within the desired temperature range, as such it is important to assess the system's ability to create control the relative humidity within the enclosure. The humidity control tests were conducted with an additional humidity measuring system placed on the exterior of the incubator system to act as a control and measure the humidity on the exterior of the enclosure as the humidity within the enclosure is raised autonomously to the set threshold value. The tests were conducted over a 10-minute period with 1-minute intervals between readings. The readings of both the internal incubator humidity and external control humidity were recorded and tabulated in Table I.

TABLE I. HUMIDITY CONTROL TEST RESULTS

	Humidity/%									
Incubator System	65	76	85	90	95	95	95	95	92	95
Control	65	65	66	66	66	66	66	66	66	65

Tests were conducted by setting varied threshold humidity values and monitoring the system's ability to create a microenvironment within the enclosure within the set humidity range. Table I and Fig 5. illustrate an extreme of the tests conducted where the upper threshold value was set to 95% and the lower threshold value was set to 90%. From Fig 5. the initial humidity reading within and around the enclosure was 65%. Upon initialization of the system, the humidity rapidly climbs to a reading of 76% within the enclosure by the 1-minute mark, whereas the control reading remains at 65%. The rate of the change of the humidity reduces slightly, past the 3-minute mark compared to the rate of change prior. Within the initial 2-minutes, the humidity in the enclosure rises 20%, giving a rate of 10%/min, whereas the from the 3-minute mark to the 5-minute mark, the system indicates a 10% rise, giving a 5%/min rate of change, half of that observed in the first 2 minutes of operation. At the 5-minute mark, the humidity in the enclosure reaches the upper threshold value of 95% where current is cut off from the humidifier in the system. Due to the humidity in the enclosure remains constant at 95% for 3 minutes before dropping to 92% at the 9 minute mark, where the system automatically reactivated the humidifier, bringing the humidity back up to 95% for the final humidity recording at the 10-minute mark. Throughout this, the control humidity senor placed on the exterior recorded a 1% increment to 66% from the 3-minute mark, which remained constant for 6-minutes before returning to 65% for the final recording at the 10-minute mark.

This test and other tests done at different threshold values indicate that the system is highly capable of creating a microclimate of varied humidity's as required by the infant. The high humidity test conducted and recorded in Table I and Fig 5. show the system's ability to create an extremely high humidity environment within the enclosure within a very short time period, indicating that any other desired humidity ranges below that shown can be achieved and at a high rate of change, crucial in situations where immediate incubation of a neonate is required. The numerous tests conducted at varying humidity's indicate high reliability of the humidity control system and the ability for precise tuning of the humidity within the enclosure to suite the varying humidity requirements of neonates.

Neonates under 30 weeks of gestation are born with an underdeveloped epidermis, increasing the risk of high-water loss through the epidermis due to the infant's inability to regulate evaporative heat loss as well as transepidermal water loss resulting in temperature instability, heat and calorie loss. Placing the neonate in increased humidity environment significantly reduces the possibility of this occurring, however, use of the incubators is seen to slow the natural process of epidermal development of the neonate and as such, a balance must be set to allow for natural epidermal development.

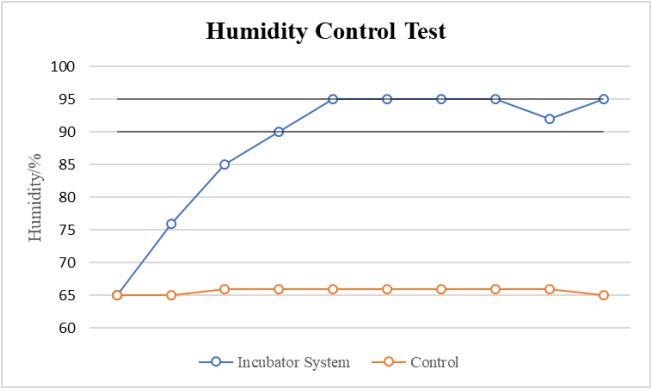

Fig. 5. Graphical humidity control test results

Varying guidelines exist on the proper procedure used to adjust the humidity during neonatal incubation, however, the United National Health Service guidelines state that incubation must commence at 80% for all preterm infants admitted to the NICU, with this humidity remaining constant

for 7 days for babies under 28 weeks gestation, after which 5% reductions are made daily until 40% humidity is reached and humidification can be ceased. Thus, it is crucial the incubator units be capable of creating and maintaining humidity's of a wide range, of which through the tests conducted the humidity control system developed in the constructed incubator system has proven capable of.

B) Ambient Temperature Control Test

To further assist preterm neonates in maintaining a nominal body temperature the temperature within neonatal incubators is adjusted to aid the infants in regaining heat lost through their underdeveloped epidermis. Much like humidity control, the temperature guidelines vary with different temperatures used upon commencement of incubation and adjusted throughout the incubation period. The developed system is programmed to actively measure the infants body temperature in real time and autonomously adjusts the ambient temperature within the incubator enclosure to maintain a nominal body temperature. It is thus crucial to assess the system's ability to reach and maintain a desired ambient temperature. Temperature control tests were conducted with an additional temperature sensing system placed on the exterior of the incubator system to measure the surrounding ambient temperature and act as a control. The incubator system was initialised with a threshold temperature of 37°C. The tests were conducted for a period of 10-minutes with 1-minute intervals between measurements. The readings from both the incubator's ambient temperature sensor and the external control sensor were recorded and tabulated in Table II.

TABLE II. AMBIENT TEMPERATURE TEST RESULTS

	Ambient Temperature/°C									
Incubator System	32	32	33	34	34	35	35	36	36	37
Control	32	32	32	32	32	32	32	32	32	32

Table II and Fig 6. detail the ambient temperature control test results, which indicate that as expected, the ambient temperature within the enclosure matched that of the exterior surrounding at 32°C.

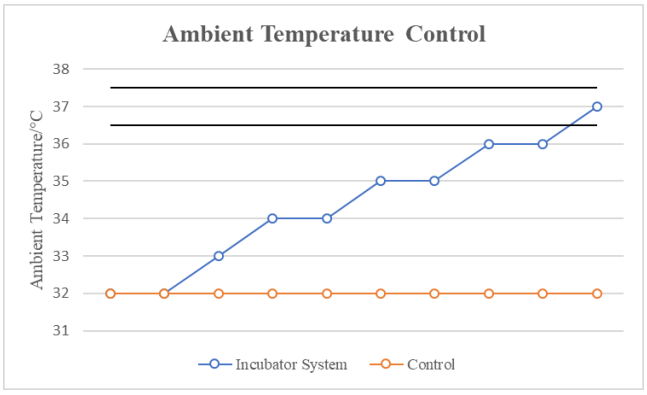

Fig. 6. Graphical humidity control test eesults

This remained constant through to the 2-minute mark where the ambient temperature began to rise at a rate of 1°C per minute, reaching 34°C by the 4- minute mark. The ambient temperature withing the enclosure remains constant for the next minute, before rising to 35°C at the 6-minute mark. The ambient temperature within the enclosure continues to rise in 1-minute intervals reaching the desired 37°C threshold value by the final 10-minute measurement. Throughout, the external ambient temperature measuring system measured a constant 32°C, illustrated in Fig 6.

C) Body Temperature Measurement Test

The accuracy of the body temperature measurements taken is crucial in the operation of neonatal incubators as their main function is to maintain the infants body temperature between of 35 and 37 degrees Celsius. The body temperature tests conducted were used to assess the accuracy of the temperature sensing component of the developed system. The tests were conducted on an adult male with no present medical conditions that may affect the measurements taken. Body temperature readings tend to vary with measurement point and are estimated to be roughly 36.2°C to 37.5°C for axillary (underarm) temperature measurements [19].

TABLE III. BODY TEMPERATURE TEST RESULTS

	Body Temperature/°C									
Incubator System	36.3	36.4	36.5	36.5	36.6	36.6	36.6	36.6	36.7	36.7
Control	36.5	36.5	36.5	36.6	36.6	36.7	36.7	36.7	36.7	36.7

The tests were conducted by measuring the axillary temperature of the subject via the incubator temperature sensor and simultaneously measuring the axillary temperature of the subject's other underarm via a medical grade digital axillary temperature sensor. The tests were conducted over a 10-minute period with a 1-minute interval between temperature readings. The temperature readings were recorded and are illustrated in Table III. Examining Fig 7. the initial Incubator System temperature reading is 36.3°C where the medical grade sensor measures a temperature of 36.5°C. The incubator temperature reading gradually rises to meet the medical grade temperature sensor at 36.5°C at the 3-minute mark.

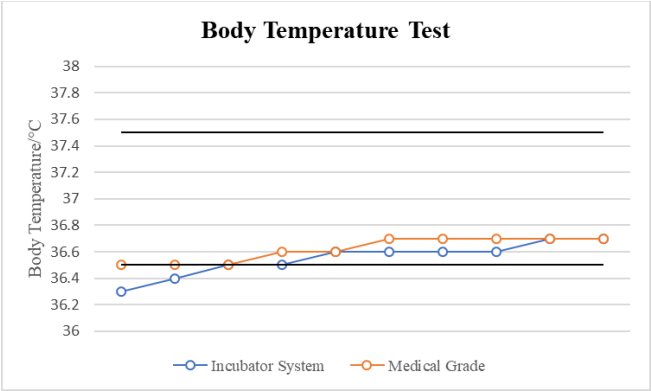

Fig. 7. Graphical Body Temperature Test Results

Throughout the test, the medical grade sensor indicated a temperature rise of 0.1 degrees before the incubator system indicated the increment, as is seen at the 4 minute mark as well as from the 6-minute mark where the medical grade sensor indicated its final temperature reading of 36.7°C roughly 3 minutes before the incubator body temperature sensor indicated the same reading. Past the 2-minute mark, the incubator system gave temperature readings within 0.1°C degrees of the medical grade temperature sensor, despite

taking slightly longer to identify the changes in temperature. Throughout the tests, the incubator system indicated temperature readings between the 36.2°C and 37.5°C normal temperature range, indicated in Fig 7. This indicates a normal axillary body temperature reading of the subject as hypothesised.

VI. CONCLUSIONS

Tthe developed system can adjust and maintain an artificial temperature and humidity within the incubator enclosure allowing for the creation of an optimal micro-climate for the preterm neonates. The developed system was tested to extreme humidity and optimal temperature levels and could achieve both within 10-minute period and did so on repeated attempts ensuring the system's reliability regarding temperature and humidity control. The developed system incorporates a heart rate and blood oxygen saturation detection system, of which indicate irregular heart rate and blood oxygen readings through the IOT application based on a given expected range set in the systems program. The accuracy and reliability of the detected heart rate and blood oxygen saturation readings was compared to that of a medical grade pulse oximeter revealing highly accurate readings from the incubator integrated system and ensuring it viability in its desired application. The developed system incorporated an IOT data monitoring system through the Blynk IOT application platform illustrating sensory data from multiple neonatal incubator units. The overall system was evaluated testing the components relating to the objectives set as well as additional components. The humidity and temperature control objective were met by setting desired threshold values and observing the system's ability to reach and maintain the given values. The blood oxygen and heart rate objective were assessed by comparing the developed system to the readings from a medical grade pulse oximeter and finally, the IOT monitoring aspect was evaluated by the retrieval of data through the IOT application for the tests conducted.

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