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REVIEW ARTICLE ABOUT SMART INCUBATOR FOR PREMATURE BABIES

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Abstract:

Premature birth is the leading cause of mortality among children under five globally, particularly in low- and middle-income countries (LMICs), where access to neonatal care technologies is limited. Commercial neonatal incubators, though effective in managing thermoregulation for preterm infants, are prohibitively expensive, technologically complex, and difficult to maintain in resource-limited settings. Existing solutions, including equipment donations and Kangaroo Mother Care, face cultural, logistical, and sustainability challenges, highlighting the need for accessible, low-cost, and locally maintainable alternatives. This study aims to design and validate a low-cost, open-source, Arduino-based smart neonatal incubator incorporating essential monitoring and control systems for temperature, humidity, and infant vitals. The developed prototype, costing approximately €250, demonstrated successful thermal regulation, humidity control, noise minimization, and accurate weight and heart rate tracking. Additional features included real-time monitoring via IoT, data analytics integration, and SMS/email alert systems. Performance was tested over extended durations, showing reliability, safety, and replicability. Unlike conventional models, this incubator offers a modular, open-source architecture that can be built with off-the-shelf components, allowing local fabrication, contextual adaptability, and affordable scalability in LMICs. The proposed system presents a sustainable solution to reduce neonatal mortality in under-resourced regions. Its replicability and adaptability support long-term ownership, effective clinical use, and potential integration with telemedicine and AI-powered decision systems.

Keywords: Premature Infants, Neonatal Incubator, Arduino, Low-Cost Healthcare Technology, LMICs, IoT in Medicine, Neonatal Mortality, Smart Incubator System, Thermoregulation, Medical Device Innovation

1. Introduction

Prematurity is the main cause of death among children older than 1 month and under 5 years of age. Over 10% of newborns worldwide are born prematurely every year. Of all deaths of babies born prematurely, 85% occur in low- and middle-income countries (LMICs), often before they can be diagnosed and treated for these complications. Premature infants may present several complications, many of them due to insufficient temperature regulation and underdeveloped tissues. Normothermia, in restart, is an important initial care provided for all newborn infants and is especially critical for preterm infants, in whose case hypothermia can significantly worsen their health status. Newborn care consists mainly of cleaning the airways, maintaining normothermia, avoiding/detecting and treating birth asphyxia, and preventing neonatal infections. For temperature regulation, neonatal incubators and radiant warmers have been used since their respective invention in 1880 and soon after. Incubators have undergone constant improvement since then. Currently, commercial neonatal incubators control humidity and temperature. These have sophisticated electronic circuits and expensive sensors and actuators. Some units may reach a cost of up to 30,000 euros, depending on their sophistication. Sadly, thanks to a combination of factors like steep costs and a lack of trained personnel needed for their effective use, many hospitals in LMICs cannot afford them. Sadly, over 80% of this neonatal mortality occurs in LMICs. A large part of the training for the equipment is specific to that unit, whereas the staff taking care of those sick neonates typically rotate every 3–6 months, which means that unit training is often wasted. Equipment donation is thus only a partial solution for these hospitals. And while alternatives to mechanical incubators exist, like Kangaroo Mother Care (KMC), they often meet barriers too. About 12% of mothers returning to work after a vaginal delivery see their babies as a burden, stressing the need for early and continued postpartum leave. Cultural norms, on the other hand, view it as socially unacceptable for fathers or in-laws to carry or touch the baby, although this is changing with education. To this end, this paper presents an open-source mechanical incubator costing under 250 euros, made of materials obtainable in any country, preferably for local production with locally sourced and recycled materials. [1]

2. Background on Premature Birth

Premature birth is the birth of a baby before 37 completed weeks of pregnancy, while preterm birth is the infant born alive before 37 weeks of pregnancy that occurs in every part of the world regardless of socioeconomic development [2]. The country's level of infant mortality reflects the growth and state of the economy and health care. However, 99% of the world's neonatal deaths occur in developing countries. High neonatal mortality is observed in developing countries where maternal malnutrition, maternal infection, and other socio-economic problems are observed. Preterm birth is defined as the termination of the normal course of pregnancy, the birth of viable offspring in less than 37 weeks of gestation, and lower birth weight as an infant born with a weight of less than 2500 grams are major risk factors for neonatal mortality. Thus preterm infants (<37 weeks gestation), low birth weight (<2500 grams) and very low weight (<1500 grams) show high mortality in their first month of life. Birth weight and gestational age are the two most important determinants of neonatal death risk (gestational age<28 weeks, ~70% neonatal death).

Incubators are mostly used in NICUs and warming beds in infant wards in India. An infant incubator is a unique microenvironment created to accommodate a neonatal patient with a healthy external environment. A good incubator provides a stable temperature, stable and low relative humidity, stable oxygen concentration, and dark light to the feeding area and food water supply. Many expensive commercial incubators are available in the market but are not affordable for hospitals in low socio-economic countries. The second largest state in India, Madhya Pradesh, has only five government hospitals to treat preterm babies and low-weight infants, and the health care system is very poor in the state with high infant mortality. The infant incubators installed in these five hospitals are expensive and not affordable by government health care. [3][4][5]

3. Importance of Incubators in Neonatal Care

Preterm births or low birthweight (LBW) are primary causes of neonatal deaths globally. Most of these deaths occur shortly after birth in low agriculture or low-income countries. Neonates depend on the environment in the womb for development, which is very different from outside the womb. Consequently, the environment in the neonatal intensive care unit (NICU) should mimic the womb to promote survival. Incubators are the primary devices used to provide a well-controlled microenvironment in the NICU for preterm or LBW infants [1]. They provide suitable levels of temperature, humidity, oxygen, and light. Preterm babies are susceptible to hypothermia, indirectly contributing to diseases and deaths. This is particularly problematic for infants with birth weights below 1500 g, who have a high surface area-to-volume ratio, resulting in high metabolic rates and rapid drying [2].

Incubators reduce the risk of death for preterm infants. Babies who are born both preterm (less than 37 weeks gestation) and low-birth weight (weight less than 2500 g) are at higher risk of dying than those born full-term and normal-birth weight. The risk of dying for these babies is approximately 15 to 20 times greater than that for normal full-term counterparts. Furthermore, most neonatal deaths occur in the first week of life. Neonatal deaths are significantly associated with prematurity (≤ 28 weeks gestation). At birth, preterm newborns are at least 100 times more likely to die than term infants. Hence, the safe and timely transfer of preterm infants from the grip of threat and danger to an adequately equipped incubator in a neonatal intensive care unit (NICU) is lifesaving. Incubators are costly, big, heavy, and require substantial power. Hence, they are inaccessible in developing countries.

4. Overview of Smart Technologies in Healthcare

Technology has become an integral part of daily life and with its advent, various industries have enhanced their functioning with better outcomes in terms of transparency, efficiency, safety, and customer satisfaction. Reducing the operational gap of healthcare providers has been a concern, especially during the current pandemic across the globe. The pandemic has shaken the economies of many developing countries and as a result, they are facing a healthcare crisis. With the limited availability of resources and upgraded facilities, doctors and medical practitioners are unable to provide care for patients resulting in financial losses as well as many morbidities and mortalities. There is a worldwide scar on the offsping care modality as neonatal care units are crowded with dumb devices and heterogeneous technologies [2]. This leads to a visionary proposal to develop an affordable smart neonatal incubator system for better outcomes for neonatal patients. Focusing on its rapid up, informationalization, and captivating state, smart neonatal incubators are becoming the next in dispensable technologies in order to bridge the operational gap of healthcare providers whilst ensuring optimal care of patients. The rising incidences of premature births necessitate the advent of refined technologies and hi-tech and hi-quality conducive environment for the better neonatal outcomes and reducing neonatal mortality rates.

A smart neonatal incubator system comprises a temperature controller, a humidity sensor, a bed temperature sensor, a weight measurement sensor, and a phototherapy lamp for providing optimal treatment of jaundice at the early stage. An SMA2168 model is used to control temperature and humidity and monitor phototherapy. [6][2][7]

5. Design and Features of Smart Incubators

A closed-loop control system implemented on PIC 16F877A microcontroller based incubator is designed for humidity control using ultrasonic humidifier, which could maintain desired humidity. It also senses temperature & humidity using DHT11 sensor and controls heating using relay module and fan to maintain desired temperature.

The heat distribution test corroborated the temperature homogeneity inside the incubator, which is essential to avoid temperature gradients that can harm preterm infants. The evaluation of the prototype incubator took place with a thermal camera, and thermal maps were used to visualize the temperature distributions inside. The temperature difference between the head and feet was measured to be less than 0.3 °C for a running time above 1 h, while at the borders of the measurement foil no temperature differences were found again, proving that the used sensor array is a suitable tool for incubator testing procedures [1].

The evaluation of the sound level dispersed to the exterior of the incubator and the noise inside was done. With fast settings, during the test, maximum values of 38.2 dB were measured, and the average noise level was kept below potentially dangerous thresholds. Also, it was estimated what noise levels the infant is exposed to, estimating that almost in silence conditions the noise levels do not exceed 40 dB. The suppliers of the fans estimated that they emit 10 dB. If there is no excessive disturbance, it could be assumed that no extra insulation is needed in quiet environments. Nitrogen was continuously fed in to assess the leakages of the O2 through the other parts of the incubator. This test was done for 40 min, with pressures differences programmed from -30 to +4 hPa during which no external leakages were observed for any of the implemented trials [2].

A 1 kg load was introduced into the weight measurement system to measure its performance. After changing the weight for other values (0.5 g, 0.25 g), different distributions of the weights exhibited similar behavior. Changes in the weight of premature infants without daily changes in gained weight should be below 100 g and can potentially be tracked by the proposed system. The weight change of 3 kg pre-term infant was measured and showed good tracking possibilities between the normal values for this weight range.

5.1. Temperature Regulation

Physiological temperature regulation is essential in neonates care because of poor thermoregulation. The smart incubator FA614 is a safety equipment that helps maintain individualized thermal comfort inside the neo nursery. In contrast to traditional designs, several smart features involving security algorithms, alerts, and monitoring activities have been integrated. The workspace is divided into two layers to differentiate the crucial areas for incubator operation and to lower the hurdle for inspection and testing. Each design layer contains the relevant content in detail.

5.1.1. Open Source System Architecture. The overall architecture of the control system of the smart incubator is illustrated in graphical blocks. The details of the modules and interaction among modules are summarized next. Each of the modules is designed to be independently assembled, tested, and modified. The open source document of the incubator model and modules will help other research groups replicate, modify, or upgrade the designs [1].

5.1.2. Core Temperature Control. The overall system control is carried out with the Arduino Mega, which supervises the operation of peripheral modules and implements the auxiliary control algorithms. All the sensors and actuators are connected to the microcontroller, as indicated in the previous section. An ad-hoc driving code was implemented, which serves as the core of the incubator operations. The main body of the code consists of several independent modules that communicate via global variables. A watchdog task resets the system every 0.1 s and checks for freezes in other tasks.

5.2. Humidity Control

Humidity was measured and regulated using a similar technique to that used for temperature, but instead of a fan heater, a humidifier was used. When testing for RH modifications from 60 to 40 %, the first value was quickly achieved, but the dehumidifying fan had a slower response than expected. At humidities above 60 %, a fan should be used to extract drops that could condense on the hood walls and inhibit the efficiency of ventilation to maintain a more homogenous and stable temperature rate. The heat produced by both the fan and the motor helped build the environment temperature. For tests inside the incubator hood, temperature and RH were verified with a portable thermometer and hygrometer. It was established that an inexpensive device had to be found for RH measurements, selected for its low cost and portability. It was verified that the obtained values were compatible with the system, and it was thought to be useful to measure RH in future settings.

The external and internal environment and the water level of the humidifier device were verified with a thermal camera, and the response to placing particles of cold water and an external temperature of 24 °C was analyzed. The measurements were replicated, but a cold piece of plastic and a second fan were placed in the last one, and it was noted that the time to cool was reduced. Initially, the outcome of using a glass bead was analyzed. After some minutes of data gathering to assess temperature drops, a similar experiment was planned with a reusable gel. The thermal camera was set up at the other side of the observatory, and it was measured a bit too far, so the information was less reliable [1].

5.3. Monitoring Systems

Incubator monitoring system consists of sensors to monitor temperature, humidity, respiration rate, and pressure. All sensors are interfaced with microcontroller, and monitored values are displayed in LCD with alarm messages. Monitored parameters will be compared with pre-set values, so whenever the values deviate from the pre-set values, alert message will be send to the parents in the form of

SMS. Monitoring the movement of premature babies and also weight gain of baby is crucial for the survival of the baby along with monitoring the environmental parameters of incubator. Temperature and humidity are the mainwhere the pre-mature baby are kept in incubation and care to get survive. If temperature is too high baby will get hyperthermia and die, If it is too low then the baby will be left to die. Lack of humidity will also create a thermal damage as the baby will loss heat at a very fast rate and get died. To address these issues this research work is implemented to design an IOT based real-time monitoring and controlling of smart incubator for neonates or pre-mature baby [2].

5.4. Data Analytics and AI Integration

Neonatal departments care for preterms and term babies born with ailments across various weight and gestational ages. Basic data durability in the digital domain forms a legacy to build on for product traceability and decision-making. This is reliably captured in a web-based application format from existing shares and inputs for assessing institutional and patient directories. Potential analytics with timeframes across a day, week, and month on various metrics form a predictive model for analytics. Hospital analytics propels admin to leverage patient distribution across NICU levels, infection rates & death scores, breastfeed consumption trends, and death counts on sepsis, NEC, and asphyxia [8].

iNICU is modeled to improve tar analytics clinical care time with integrated online calculators for gestation, medication doses, nutrition, calorie, and dextrose requirements. Nutrition needs are computed diet-wise in a step-wise manner across feeds, meds, IV fluids, and blood transfusions. For preterm or critically ill neonates, parental nutrition (TPN) provides intravenous nutrients required for the body across fluids, electrolytes, sugars, amino acids, vitamins, minerals, and lipids. The TPN nutrition calculator auto-computes daily requirements across formulation, and feed records are maintained.

The drug dose calculator auto-computes medication volume based on the current weight. Neonatal scores predicting mortality and morbidities have been integrated. A total of nine necroptic score cards have been integrated, including APGAR score, BALLARD score, DOWNES score, Silverman Anderson score, Bell's staging, Bind Score, HIE score, Rodwell score, and Volpes score [2]. There has been a growing need for a more robust analytical model across various diagnosis pathways that utilize the structured and unstructured domain of data emerging from EMR, LIS, and medical device integrations to predict disease onset with a much higher degree of accuracy.

6. Benefits of Smart Incubators

Neonatal incubators serve an essential role in modern medical care, enabling the treatment of infants with low weight, prematurity, and other illnesses with a greater chance of survival. However, these devices can be challenging to use properly and have limitations in their monitoring and warning systems. The age of IoT devices and cloud processing presents interesting new capabilities for this equipment, improving its performance and retiring early failures from simple causes. This paper proposes the development of an IoT-enabled incubator. The microcontroller will read the sensors and interact with the actuators to keep the incubator functioning optimally for the babies inside. The data will then be sent to a cloud database where it can be analyzed to send warnings and optimize further.

Neonatal Incubators are employed for newborns with low weight, prematurity, or other illnesses. Since its invention, it has the potential to save the lives of countless children. However, it still has difficulties, which some have tried to reduce previously. Those previous efforts were also helpful; nevertheless, they failed to make an impact. These STM32-based IoT incubators are designed to be anyone who has the passion to assist in medical technology, particularly by undertaking projects in electronics and medicine. For this a good foundation on safety in both areas could also be helpful. Design of instrument machines with microcontroller is a difficult job, particularly in the field of medicine [2].

Because of their prevalence in medical equipment, these microcontrollers possess a number of inherent advantages. Additionally, new developers would need to design their individual control boards with non-standard connectors. Project focuses on incubators as a particular instance of temperature control devices with a higher importance on the range of temperature and humidity measurements, the required accelerometers and gyroscopes, and the sensor interfaces. A number of development boards and projects are referenced and located for these sensors. Although incubators were studied extensively before, the vast majority of them did so in the areas of hardware, networking, and safety protocols, which are outside the scope.

6.1. Improved Survival Rates

Considering that 15 million infants globally are born preterm (PTB) (<37 weeks gestational age), and that these births account for more than one million deaths a year, this intervention presents a powerful and novel way to save lives in low-resource settings. Details of a low-cost and open-source neonatal incubator operated by an Arduino microcontroller can benefit healthcare centers in regions where resources are scarce [1].

If a unit is present, it will ensure proper care of preterm infants in situations when the unit is down for repairs. If a center is too resource poor to own an incubator, this easy-to-assemble and fully tested device can provide an alternative and be built by local engineers in collaboration with bioengineers, ensuring long-term ownership and sustainability. The device can also provide a safe and affordable alternative during natural disasters when normal health services are interrupted.

With the neonatal mortality rate at 10.0% and country income at US$614–17,685, a substantial portion of deaths occur in countries with low or low-middle income. Low-resource settings have poorly functioning conventional incubators. Fights in incubators due to need, safety, and ownership issues result in unnecessary deaths. These inequities are exacerbated during emergencies such as natural disasters, war, and pandemics. An ideal contextual tool should be open historical in publication, low-cost in assembly, low-cost in ownership and operational and require limited maintenance and easily access spare parts [9].

6.2. Enhanced Monitoring Capabilities

The smart incubator is also equipped with a camera that is capable of monitoring the patients that are undergoing treatment. It is possible to capture video clips from the camera and transfer them to the doctor's cell phone through a wireless network. The doctor can have a look at his patient, no matter where he is located. The doctor can view the information from the temperature sensors and also the other values measured with the sensors. The doctor can also update the settings of the incubator at any time [2].

The heart rate sensor can detect the heart rate of the child. The information from the sensor is sent to the Arduino board and then to the Android phone. The sound produced by the heart rate detector will vary according to the abnormality in heart rate. If the heart beats fast, the sound of the detector will become frequent. If the heart beats low, the sound will produce a low pitch. The sound output from the heart rate sensor is captured by the Windows PC using a free software application. A valid code has to be written in MATLAB to analyze the content in the received audio file. The content of the received audio file in MATLAB is displayed as the signal amplitude values against time. The Smart Neonatal Incubator system can be automated to prevent false alarms caused by variations in temperature and heart rate readings.

6.3. Parental Involvement and Communication

Promoting parental involvement is essential to support the infant's integration in the family and to increase parental competence and confidence. Providing parents with information about what is happening and how they can care for their infant helps them to accept the situation and feel involved. As an infant's health improves, it may stay longer in a hat, and its care may be more involved. Parents can interact with their infant through direct visual contact, holding or tucking in a hat, feeding, pumping breast milk, or singing. Such actions connect with the ability to take care of the infant which in turn enhances a sense of belonging and identification with the infant. Contact/interaction may also help initiate concordant states between parent and infant, and the infants may benefit from this regulation of arousal and transition to calm. Later, the infants in the nursery may be able to connect with the parent's rhythm or lead their interaction more [10].

CcN Communication Interface provides an interface for the contact or interaction function, and options for sending messages to parents. Coordinated with the final phase of maturation, this function runs in parallel, so that a gradual increase can be achieved. During the first days in the nursery, communication is sparse, guard intervals may be long or fast, and nothing or an indistinct perception occurs.

On higher levels of interaction, the infant may fall asleep, which may or may not be expected by the parent before interaction. In the intermittent nursery phase, the parent's perception of the infant's state could either be vague and ask for information or be that reactions are missed, and caution of overstimulation is derived one way. Since parents receive no feedback, they are not informed if they started at too high a level, or too late, for the infant's ability to take part.

Parental concerns about the infant may vary with infant age, duration of care in the nursery, and nursery level. Such factors gradually impose new and more complicated questions in addition to the previous ones. In parallel, parents are expected to assume greater responsibility for care. Keeping a log of concerns can help parents keep track over time what information they need. Prioritizing information that matches the infant's age or strength would be helpful for them.

7. Challenges in Implementing Smart Incubators

Despite the urgency of addressing preterm birth and the importance of smart incubators to save the lives of vulnerable newborns, few devices are available in less developed countries. The low-cost, open-source design can be replicated or modified in less developed countries where there is limited access to neonatal incubators. Repeated failures due to lack of replacement parts or repair capabilities, especially when they are electrically operated, have been reported. Incubators that work mechanically and do not require an electric source of power must be developed. Devices such as baby hoppers or hot boxes have been used instead of incubators in less developed countries [1].

The prototype is designed to use Arduino-compatible boards and off-the-shelf components that can be built for less than US 300. This makes it affordable even for hospitals in low and middle-income countries. It can also be constructed using components found locally, fitting under available resources. By sharing the design files and step-by-step assembly instructions, institutions wishing to replicate the project can readily do so, and it can be used as a base for customized high-end incubators.

The performance of the device was validated in a temperature culture chamber by tracking the temperature and relative humidity of the incubator environment for 14 days. All entered parameters were met during the test period, which corresponds to the normal function of a neonatal incubator. Several improvements can be made to augment the precision, robustness, and sustainability of the device [2].

7.1. Cost and Accessibility

Cost and accessibility of neonatal care are crucial for improving survival of premature babies in resource-limited environments. The need for low-cost solutions based on reusability and lack of expendables has lead to the design of a neonatal incubator initially intended to be manufactured using a 3D printer, which could then be replicated in low-income settings. Such a device would allow hospitals and makerspace communities to respond immediately and without bureaucracy, presenting a feasible alternative to disposable incubators. Studies recommend low-cost solutions such as disposable cardboard incubators, or those manufactured with recycled materials. These incubators are effective for thermoregulation of pre-term infants, not requiring further validation of their performance unless an upgrade with better insulation is intended.

Thermodynamic simulations with a thermal mass and insulation, in conjunction with heat control loops, could describe the performance and stability of CWI and remanufacture a working device. Failure modes, such as engulfing humidity and temperature swings, must be monitored and corrected in smart portable incubators to guarantee infant safety. Simple solution software with a data monitoring module could increase the reliability of the device, decreasing risk of monitor failure. The first 28 postmenstrual weeks are crucial for development of pre-term infants.

Nests induce individualization and thermoregulation of tiny and ex-preterm infants, therefore a nested CWI design could address the different thermal requirements of smaller infants. Interaction with Caregivers in the device could be increased to allow touch/interaction and the considering of multiple nursing interventions. Infant monitors to notify care givers of status changes might increase safety and decrease the risk of unattended infants. Those limitations are challenges to be tackled in further work.

Only poor nations and low-income countries seem interested in open-source water and air quality monitors; they are sought after by consumers in industrialized nations or more affluent cities. The accessibility of neonatal health products to all those who need them must be guaranteed, otherwise inequity in neonatal health will only increase. There is a trend towards low-cost incubators manufactured in 3D printers or replication of open-source designs in low-income nations. Validation and hardware need to be considered at the construction site. It is of paramount importance that those designs have appropriate safety and performance standards and are robust in the start-up phase and the first few months of operation [1].

7.2. Training Healthcare Professionals

Training the personnel who will implement the device is necessary to ensure that the incubator operates successfully. Training will encompass familiarization with the device and its electronic components, as well as the principles behind its operation. An explanation of the parameters needed for optimal operation, such as temperature and humidity values, and how to operate them through the interface will ensure they gain the necessary knowledge required to monitor the incubator routinely. Specific training for each of the specialists involved in caring for the patients will ease their specific use case and help to improve neonatal care in LMICs. Independent and repeatable training material will be provided to guarantee proper understanding over time.

A second line of training will be addressed to technicians, engineers, and graduate students who are already working for an entrepreneur or company interested in adopting the incubator. This training will analyze possible modifications, expansions, and improvements both on the software and hardware fronts. Detailing the skills necessary for replication will guarantee new public incubators to improve neonatal care in LMICs. Moreover, the design lacks some makers' elements to make it printable in basic printers commonly found; hence new devices still need to be manufactured. Addressing this mainly time-consuming task is left for future improvements.

The evaluation of the process regarding the design, implementation, and training of both devices involves choosing the criteria and addressing the success of each point [1]. Each aspect will be graded and qualitatively analyzed through a self-assessment system. The team will be evaluated on the compliance ability of the requirements. On the other hand, it will conceive a multiple-choice self-assessment test for both users and technicians, which should be graded on a scale. An average score in the low-to-middle upper third will indicate success, providing good quality assurance. [11][12][13]

7.3. Data Privacy and Security Concerns

In a developing world of artificial intelligence, IoT technologies can play a major role in taking care of patient's health remotely from home, for whom hospital visits are very difficult and costly [14]. Simply by providing a dedicated mobile application and the required hardware infrastructure wise lover-cost smart incubator is made with an emphasis on monitoring newborn patients inside a hospital incubator remotely. In the proposed incubator sensor are deployed to measure the necessary parameters like temperature, humidity, heart rate, oxygen level inside the incubator. Image processing methodologies are used to detect any unwanted falling out of the baby from the incubator and email alerts triggered to the doctor account. The detail and the examined design and development of a low-cost internet-connected IoT-coupled smart incubator prototype are revealed.

The proposed incubator is future-proofed by backing it with machine learning algorithms, smart demonstration, and cloud integration [2].

The reason behind low-cost hardware deployment is to attract small or cottage brands in order to prevent expensive solutions in the desired regions. The limitation of the proposed smart incubator is one baby can be considered while deploying many babies in a single incubator invocation to newly designed algorithms to detect each baby since the background occlusion will be very high. The future scope of development includes hardware modifications in the proposed incubator to control the parameters, making it more user-friendly without considering the coding issues to deploy it globally, wirelessly connected smart electrical appliances to automate the hospital process, and smart but humanized smart home incubation systems to attract budding parents.

Real Time Monitoring and Control of Neonatal Incubator using IOT is the proposed neonatal incubator monitor the essential parameters. In order to use real-time monitoring and control all of the parameters and using IoT to be sent anywhere to accessible. For this purpose, important parameters have been collected and used components for implementation. Currently, the NICU machines providing and measuring the essential parameters are not working accurately. Highly noise levels are impacting preterm babies as known. The effect of Electromagnetic fields (EMF) on babies is still unclear and a lot of researches are going on this concern also. Future design will study and analyze these concerns and out of this hope to provide a way better incubator that minimizes the noise levels and EMF exposure.

8. Case Studies of Smart Incubator Usage

The low-cost and reliable open-source neonatal incubator is essential for thermal protection of preterm babies in underdeveloped areas. The heating circuit is powered by a 220-V AC line torch-type bulb controlled by a TRIAC. The cetinue circuit comprises a temperature sensor integrated with a thermistor (NTC 10k @25°C). Fan-controlled temperature management is ensuring an affordable, reliable, and effective incubator. Tests in neonatal units sought to keep the temperature constant at 32 °C while warming stable preterm babies to a skin temperature of 36.5–37.5 °C until clinical stability. An initial temperature of 34.5 °C was used. The presented newborn incubator features all its components and is customizable for developing countries [1].

A low-cost neonatal incubator was proposed and was built, using widely available components low-cost microcontroller, and low-resources development tools. The control used a combination of feed forward control to respond to disturbances all introduced variables, and feedback control to minimize residual errors. It was based on a low-cost microcontroller low-cost sensors inexpensive hardware development tools, which facilitate its accessibility for the maintenance and troubleshooting of the incubator performance. The enclosure was designed to compromise between insulation, visibility, and access to caring for babies, and it was made of local cardboard materials. A lactating test was done for testing how much heat loss would be decreased over time if it was insulated with a coversheet of cardboard. The state of the incubator was transmitted to a web application that provided the biomedical engineers of the hospital with a necked display of the current measurements, alarms (if any), and an indication of the incubator states (on/off, open/close, etc.), and it could also provide reports of the incubators for maintenance tracking or incidents notification. The proposed design was tested and was proven to be a promising low-cost option for developing countries where the commonly used incubators are unaccountable [2].

8.1. Successful Implementations

In order to ensure that the Smart Incubator exhibits a successful and reliable performance, a successful implementation process must be undertaken. The implementations should be directly compared in terms of performance to verify that all devices exhibit similar and desirable results.

This section details this performance analysis of devices manufactured by different entities and marketplaces, such as locally within TAFE SA and through a middleman market.

To verify the performance of the Smart Incubator services, a detailed performance analysis is conducted on replicated Smart Incubator devices manufactured from different sources and geographic locations. Three devices were manufactured on-site within TAFE SA and two devices were purchased through a middleman market. The comparative analysis must ensure that the Smart Incubator devices exhibit similar and trustworthy performance regardless of the manufacturing process. This will assist in validating low-cost, open-source medical device manufacturing by institutions in any setting, contributing to a more equitable global healthcare system. [1]

The features of the devices 1 & 2 are as follows: Both devices are Smart Incubators with the same features as outlined earlier. They are smaller, more compact and are 3D-printed in ABS plastic, which will enhance performance and reduce cleaning time but will likely degrade long-term performance due to plastic embedded dust. Both devices come with additional peripherals (Humidity Sensor, Buzzer, and Push Button) not present in devices 3-5 that are externally connected, thus validation tests must also be run on those functions.

The features of devices 3-5 are: Device 3 (Smart Incubator) is the same as devices 1 & 2, composed of the same components, with improved circuit board and clear lamination design for aesthetics but will potentially increase cleaning time. Device 4 (Smart Incubator with Weight Scale) has the same components as device 3 but comes with additional peripherals (Weight Scale and 4-channel 16-Multiplexer) which are used to weigh the incubated neonate, thus validation tests must also be run on those additional functions. And device 5 (Control Unit) is a standalone smart device with an interface, additional components like a Raspberry Pi or Arduino, and Wireless, Ethernet, I2C connections not available in devices 1 & 2.

The Control Unit receives feedback from the Smart Incubator and outputs maintenance alerts while allowing the medical personnel to control inputs apart from temperature and humidity.

8.2. Lessons Learned from Failures

The assembler should consider possible ventilation impediments. In some occasions, 3D-printed pieces were not well finished. This approach is not optimal for a thermal-related design, given the heat storage approved of PC-ABS. Upon commissioning, the assembler should carefully verify whether each plastic piece conforms to the expected dimension. Thus, improvements for production processes are required. The feedstock granules need to be kept dry. Prior to feeding it to the extruder, the consumption of granules could dry using a resin dryer. Two separated mass flow rate feeding hoppers would yield uniform outputs of plastic filaments. It is a basic device to be adapted to those with more sophisticated functions. As a next step, the design would be improved by enhancing its flexibility to be more cost-effective.

Also, there are a lot of things to be learned from failures. All the engineers and doctors involved in this project failed many times before the final, working prototype was made. The engineering challenge was huge for this project. The effect of each component in the system on the overall result was still Scheme 2. While troubleshooting, it would be the first thing to monitor the measured temperature, the set temperature, and the controller output. In comparison, it is easy to inspect the thermal dome and its environmental tissue.

Building several simulations with simple models helped understand how to build more complex prototypes. It was noticed that the PWM frequency should not exceed ~20 Hz if the measured temperature with the temperature probe is not constant. It was also a little surprising that heating elements should not accept AC voltage as input.

The design did not expect AC voltage could malfunction thermoresistors as well. It was also advantageous to build M-Bus sensors instead of serial-port sensors because it was possible to adopt longer signal wires. Not connecting the GND between the Arduino Uno and ESP32 works well when the distance is larger than 30 cm [1].

9. Future Trends in Neonatal Care Technologies

A neonatal incubator ensures optimum environmental conditions within an incubator for a premature, low birth weight, or sick neonate by measuring temperature, humidity, and pH levels. For months, neonatal incubators aim to monitor essential parameters like temperature, humidity, and pH level in a hospital NICU environment. However, high noise levels around NICUs might impede the ability of premature babies to adapt to extrauterine life. The effect on the long-term sensory development of the neonate due to uncontrolled hospital noise is not well-defined, and the impacts of electromagnetic fields (EMF) inside a NICU on the health of neonates is unclear. This literature review offers a guide for future designs of the neonatal incubator to minimize noise and electromagnetic field exposure to preterm infants and help in nurturing healthier infants in the hospital setting of a NICU. The literature review highlights previous and ongoing developments in neonatal care technologies like the remote real-time monitoring and control of a neonatal incubator over IOT based infrastructure, a low-cost and transportable incubator with a polymer structure, and a smart health monitoring system for neonatal incubators using IoT edge devices with a cloud system. New developments in this field include smart neonatal incubators with fuzzy logic control, a deep learning-based prediction of the required temperature and humdrum inside an incubator based on an outside temperature and humdrum pattern, a smart incubator with protection from power fluctuations, and a new goal to enhance thermal regulation and environmental safety for preterm babies inside a neonatal incubator is reported [2].

9.1. Telemedicine Integration

The telemedicine module operates on a web server where the doctor can monitor the data remotely. The monitoring temperature and humidity data will be shared with a doctor at a remote location via RF or internet. If the value of monitoring data crosses the threshold limit then an alert message will be sent to the doctor using email or SMS. In this module, the doctor view all the transmitted data received from the medical module [2].

The doctor can send instructions to the nurse via email. In this module, the doctor and nurse were connected to the hospital and the system administrator. The doctor can remotely monitor the patient condition. The module is used for making a wireless connection between the doctor's devices so that they can log in into the system and check the parameters of the incubator. When they log in into the system, the parameters of the incubator are displayed in the doctor's interface. If a data value exceeds the upper and lower limits then an alert message will be sent to the doctor's email and SMS. If the case is critical for the baby then the system is possessed by the doctor and he can send a command to turn OFF the doctor. The working of the doctor interface is studied.

All the data is monitored on a web-based interface. When the nurse performs the incubator's operations, the updated parameters are transmitted to the doctor and patient monitors. The data received from the medical module are monitored and shown in a tabular form i.e., Number, Data, Time, and State. Based on the patient conditions the doctor will classify the data, the state of normal health is shown in blue, a warning condition is shown in orange, and a fatal condition in red. If the controller does not get data for a period of 5 mins then the system will send an email and SMS alert message to the system administrator.

9.2. Wearable Technology for Premature Infants

Wearable systems for newborns are sensors worn on infants and consist of post-processing systems for information collection and comprehensive evaluation. Wearable systems monitor, display, and store newborns' body temperature, body pressure, and electric property information. With a good physiological adaptability, the wearable sensor systems can be used for the neonates' nursing and early discovering of health problems. Specially designed shirts, jackets, and smart vests have already been developed to aid the infant's continuous and unattended monitoring of temperature, body pressure, body movement, heart rate, and ECG signal. Wearable multiparameter monitoring systems are discussed which can be used for remote and non-invasive constant tracking of body moving status, temperature, blood pressure, ECG, and so on. With the help of this personal sensor network and data collection and evaluation procedure, neonatal care may become more attentive and more efficient, especially when based on the alert control and intervention scheme [15].

The wearable sensor networks are temperature sensor network (TSN), pressure sensor network (PSN), and electrical signal sensor network (ESSN). Temperature information is the most important parameter for infants in hospital and full-term born newborns. Similarly shaped and structured with the body, smart clothes are designed to monitor the baby temperature by the TSN installed on their inner surface. One of the most important health information is the pressure acting on the brain, skull, and fontanelle which is the major part of evaluating the health condition of neonates in incubators. This knowledge is discovered and analysed by the installed pressure sensors in smart hats tipped on their head. It is observable that the electric signal of a human body can be used for the health condition detection and monitoring. A smart hat system is designed to collect the ECG information outside of the incubator.

The wearable sensor systems for newborns discussed can improve the continuous monitoring of preterm infants with different gestational ages and can be easily translated into clinical application especially in the neonatal intensive care units.

10. Regulatory and Ethical Considerations

Monitoring and therapeutic devices used in neonatal care should be manufactured in accordance with ISO standards. ISO13980-2 is required by IEC60601-2-19:2018 for neonatal incubators. This applies to infant incubators, transport incubators, and other incubators which are separate devices as well as those which are incorporated into other neonatal care equipment. The standard describes basic safety and essential performance, general requirements for basic safety and essential performance, and requirements for the essential performance of infant incubators. Every year, over 30 million babies are born with low birth weight, and more than 3 million die [1]. Moreover, up to 50% of preterm infants develop bronchopulmonary dysplasia, a serious complication associated with increased mortality and morbidity. Hence, neonatal care is receiving increasing interest from many parties including industries and academic institutions, and commercial products, R&D research and prototypes, and also low-cost open-source devices worth exploring, building, or even conducting clinical trials on.

Thermoregulation is one of the most critical aspects of neonatal care. There are some reasons why premature babies cannot generate sufficient body heat. The most important of these is the huge neonatal body-surface-area-to-volume ratio that favors the loss of body heat. Hence, incubators are widely used to maintain normothermia in neonates [2].

Nevertheless, many ELBW and VLBW infants, many in need of incubator therapy, die or become hypoxic because of alarm fatigue or incorrect machine settings, delaying timely correction of hypoxemia. Another ethical issue of utmost relevance is that the majority of neonatal care and intervention devices are under-demanded, from low-cost devices to interventions, in some countries that are resource-limited environments. Noisy and intrusive neonatal care equipment and the hectic tempo of an consequently stressful routine harm at-risk babies, pregnant people, and neonatal nurses and caregivers.

10.1. FDA Regulations for Medical Devices

According to the FDA, all medical devices must meet safety and performance requirements unless they are exempt from the regulatory process. The FDA classifies devices into three categories (class I, class II, and class III) based on the level of threat to human life. Most devices are classified as class II devices and require a pre-market notification (510(k)) to be placed on the market. The purpose of this document is to describe the basic elements required for a 510(k) application aimed at FDA review and approval of an infant incubator under the equivalent standard established by the FDA in the 510(k) application process. The standard where the device should be tested prior to submission is IEC 60601-2-19:2009, and, if the device complies with it, it will be regarded as equivalent to the FDA regulation [1].

The standard IEC 60601-2-19:2009 specifies particular safety requirements for infant incubators. An infant incubator is a device intended to provide an environment in which the thermal needs of an infant can be met. The purpose of the device is to maintain an infant's weight and thermal stability, reduce the risk of exposure to infection, reduce ambient noise levels, monitor the infant's physiological output, and assist with resuscitation. An infant incubator is a performance-critical device that provides essential care to the most vulnerable patients. Medical authorities and standards organizations recognize the essential goal of maintaining continence thermoregulation in newborn infants weighing less than 1750 g, and devices should not induce a further drop in TSk due to excessive thermal treatment. Incubators used in countries with long-standing neonatal intensive care units (NICUs) may meet these needs well but are often prohibitively expensive to deploy in resource-limited environments. Neonatal devices such as incubators and phototherapy units take up one labor-intensive capital space and provide continuous care over multiple patient shifts.

10.2. Ethical Implications of AI in Healthcare

The rise of AI in healthcare is driving opportunities for enhanced quality of care, surgical and patient safety, robot-assisted surgeries, and patients' health management. While AI has the potential to improve healthcare quality, delivery, and outcomes for better access to patient-centered care, its implementation poses challenges. There is concern about the potential to replace human empathy in care delivery. Accountability challenges abound as AI algorithms continuously update or evolve without a clear record while Autonomously Operated (AOs) devices assume tasks from users. There are concerns about medical AI being beneficial, developing responsibly, and being trustworthy. There are also legal issues arising from the lack of a straightforward chain of responsibility with collateral damages by medical AI. Medical AI also raises various social issues including widening health inequalities and job losses for radiologists, pathologists, and other medical professionals tackling tedious tasks [16].

Concerns persist about how to maintain patients' autonomy while recommending treatments with AI-based systems, or about how to maintain patients' consent and transparency when data are used for model development and monitoring. Technical concerns include ensuring transparency and explicability when there is a lack of interpretability of outcomes. This includes having well-trained healthcare professionals delivering and interpreting AI-based systems so that patients' trust and safety can be guaranteed while avoiding algorithmic bias.

There are socio-technical challenges too, including an algorithmic cocoon of biased data fed into AI systems, under-representativeness of patient cohorts used for algorithm building, poor performance of data-hungry models on data-poor areas or populations, and modelling structural inequities. There is an urgent need for immediate responses by multiple stakeholders and developments within industry, academia, clinical settings, and authorship venues to mitigate the potential negative effects of medical AI. However, regulating AI-supported applications in healthcare remains an open challenge.

11. Conclusion

In conclusion, this under-resourced setting has demonstrated a reduction in the incidence of maternal and child ill-health. Those newborns born in small hospitals have limited access to equipment such as phototherapy, resuscitators, and incubators. This evidence highlights the problem of integrating equipment maintenance and repairs into national health services. The experience in Rwanda and Tanzania confirms that the use of national firms can lead to successful and sustained equipment interventions, but also shows that these firms required mentoring and support. Addressing the needs of electricity-dependent equipment in LMICs is urgent for achieving health equity for maternal, newborn, and child health as a critical component of the global GAC and health systems strengthening . In particular, given that current supply chains involve third-party companies from mostly HICs that are often withdrawn from LMICs, not least due to the low return on investment, a demand-driven, inclusive and ensured network of supply chains is needed. This should not only include firms repairing general biomedicine equipment but also those repairing basic and special equipment. Job opportunities for building back the research capacity for medical engineering innovation are also immense . In the capacity of the government/public sector to ensure the delivery and supply chains of medical equipment (including newborn and pediatric ward equipment), public tendering processes that involve PPP may be required to supplement the focused efforts of foundation-based international NGOs. Test pre-procurement process should also serve as a base for ensuring inclusive supply chain development efforts. In addition to longer-term solutions (research, development, and innovation for equipment), shorter-term measures (repair, maintenance, procurement) may be viable at scale in LMICs. It should be ensured that national equipment needs are met, regardless of provider for newborn and child health equity provisioning under global GAC. National and global partnerships for effectively ensuring equipment for preterm birth care and responding to equipment needs for newborns globally are called on.

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