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INCUSENSE: A BABY INCUBATOR WITH REAL TIME MONITORING & REGULATION OF VITALS

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Abstract
Premature birth rate in Pakistan is alarming, with a study of data from obstetrics departments revealing that over 21% of more than 1,700 newborns were premature. A UNICEF survey on newborn health confirmed that preterm birth was the leading cause of infant mortality in 2015, accounting for over 39.3% of cases. Premature Babies, particularly those born before 37 weeks of gestation, often need oxygen therapy or supplemental oxygen due to their underdeveloped lungs' inability to perform necessary respiratory functions. Traditional neonatal incubators continue to have manual setting for the level of oxygen, which in practice results in some variation in patient care. Therefore, there is a need for intelligent incubators that can regulate oxygen saturation autonomously, to stabilize the results for hypoxic infants in particularly those, born between 34 and 37 weeks. This project will deliver a novel intelligent neonatal incubator, which provides a safe and stable controlled environment for preterm neonates by adjusting the temperature and humidity to the ideal ranges. It allows tracking and modifying oxygen concentration on a real time basis to improve the oxygenation and is helpful for less healthcare resource limited regions. It has sensors, an EPS32 based control system for real time monitoring and adjusting, so that it can provide a stable environment. Temperature is controlled by the heater fan system; humidity control is passive and the oxygen flow controlled using an actuator-driven servo motor attached to the flow meter. This developmental approach is expected to revolutionize the care of neonates. The system has been demonstrated to accurately control temperature (±0.3-0.5°C), humidity (±0.5-1%), and oxygen delivery (±0.2-1 L/min) according to a range of baseline oxygen saturation. With such precise experiments, these control trials represent a validation in the reliability and clinical potential of the system, validating the potential of advanced control systems in neonatal care and implying further research towards even better control for system effectiveness in addition to adaptation to develop a system that will effectively control the Temperature and Humidity using the baby incubators with a feature to regulate oxygen

supply to Babies. In conclusion we found clinically significant value in this study, which can be used as an application of care of preterm babies in the NICU, by managing supply and delivery of oxygen.

INTRODUCTION

Babies delivered before the third trimester's 37th week are considered premature. The United States March of Dimes estimates that the U.S. rate of newborn mortality in 2020 was 5.4%, and 35.8% of the babies who died did so as a result of prematurity, as shown in Fig. 1 (M. Dimes, 2024). A 2015 UNICEF survey confirmed that preterm birth was the leading cause of infant mortality, accounting for over 39.3% of cases (UNICEF survey, 2015). Early diagnosis and intervention are essential for managing health issues in premature babies and improving their prognosis. Newborns, particularly those with very low birth weight, are prone to rapid heat loss due to factors like delivery room temperature, incubator type, and inadequate clothing (C. B. Pereira, 2016). These babies become more vulnerable because of a larger surface area and a thinner body with less fat deposition as an energy reservoir. This results in a decrease of body temperature by 2 to 4°C within the first 10-20 minutes after birth, which significantly increases the risk for hypothermia (J. P. de S. Caldas, 2018). However, without proper measures, this can be complicated to severe or even prove fatal (J. Smith, 2016).

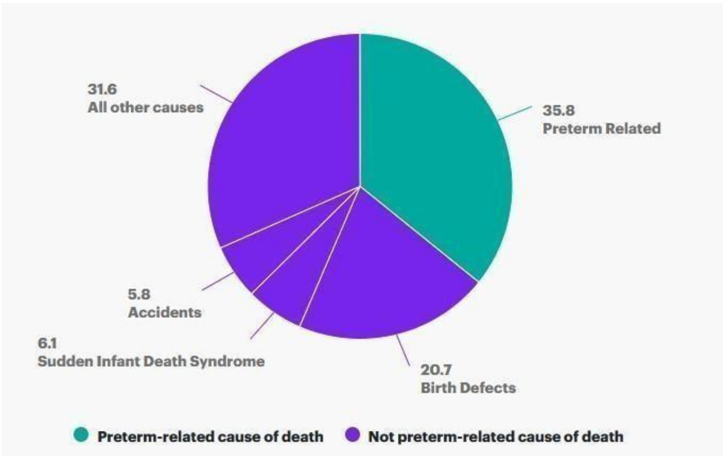

Figure 1: Preterm Death Rate, According to "March of Dimes"

This is confirmed by a UNICEF survey on newborn health, which found that preterm was the top cause of infant mortality in 2015, accounting for over 39.3% of cases, as shown in Figure 3 (UNICEF survey, 2015). These data illustrate Pakistan's considerable preterm birth rate.

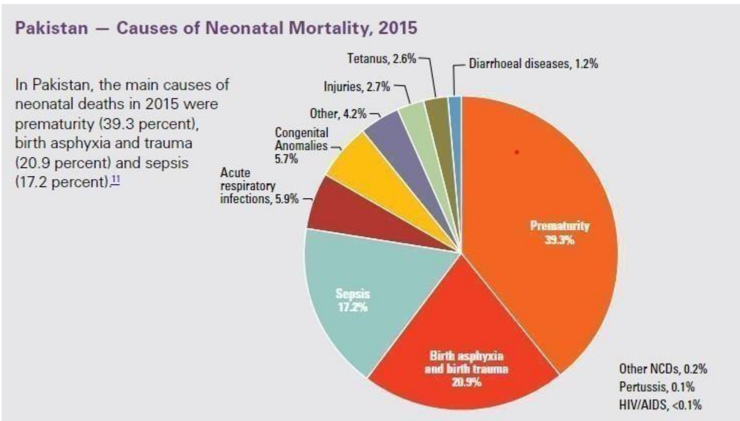

Figure 2: Distribution for Neonatal Mortality Rate

Temperature regulation is vital to the growth and development of these babies. Premature Babies may have underdeveloped lungs and can develop serious medical conditions such as respiratory distress syndrome (RDS), Broncho-Pulmonary Dysplasia (BPD) or Retinopathy of Prematurity (ROP). RDS is a result of underdeveloped lungs and absence of surfactant, which makes it difficult for the baby to breath on his own and can lead to respiratory failure. A subset of these infants needs ventilation with prolonged O2 exposure, which can also contribute to the pathogenesis causing BPD and pulmonary fibrosis, which can be dangerous even fetal.

Literature Review

The ethical consideration is critical in addressing the challenges faced by premature and critically ill newborns with sophisticated technologies such as intelligent incubators and respiratory support systems. In 2017, Katherine D. McCord discussed the ethical aspects of medical interventions and the importance of weighing technological development against ethical aspects, particularly when treatment might prove futile (McCord, 2017). This ethical approach is integral to the deployment of such sophisticated technologies as intelligent incubators and continuous positive airway pressure (CPAP) systems. In the same year, P. Wilson et al. exemplified the efficacy of CPAP in the treatment of Ghanaian children with undifferentiated respiratory distress, delivering proof of its deployment in resource-poor environments (Wilson et al., 2017). Likewise, T. Kortz et al. emphasized the cost-effectiveness of bubble CPAP (bCPAP) in minimizing invasive ventilation requirements in Malawi, further establishing its place in neonatal care in low- and middle-income countries (LMICs) (Kortz et al., 2017). By 2018, technology advancements started incorporating IoT and advanced monitoring systems into neonatal care. Megha Koli et al. presented an intelligent baby incubator with sensors and IoT features that allow real-time monitoring and control of environmental parameters inside the incubator (Koli et al., 2018). Tanveer Hussain et al. in 2019 designed an IoT and embedded vision-based intelligent baby behavior monitoring system, which delivered real-time information about infant activity to improve care in neonatal intensive care units (NICUs) (Hussain et al., 2019). 2020 witnessed additional progress in system integration and remote monitoring. Ali Ghazi Shabeeb et al. created a remote infant incubator monitoring system, enabling healthcare professionals to monitor premature babies' conditions remotely without physical presence (Shabeeb et al., 2020). This was matched by M. Nørgaard et al.'s systematic review of bCPAP in LMICs, which found that bCPAP is a cost-effective and useful intervention for the treatment of respiratory distress in children, especially in resource-constrained settings (Nørgaard et al., 2020). In 2021, L. Lamidi and A. Kholiq centered on enhanced temperature control devices in infant incubators, placing high value on accurate regulation of infant health (Kholiq & Lamidi, 2021). Building on their prior work, subsequent improvements were introduced in 2022, whereby they investigated employing proportional and derivative controls to gain better temperature stability in incubators (Kholiq & Lamidi, 2022). These studies demonstrated the ability of closed-loop control systems to enhance the precision and robustness of neonatal care technologies. By 2023, the focus of research had moved on to the integration of IoT, PID control systems, and energy-efficient design. Bambang Guruh Irianto et al. proposed a PID controlling system for infant incubators, which effectively decreased the temperature overshoot and enhanced stability of their design (Iriarto et al., 2023). Friza Servile et al. analyzed the efficiency of web-based incubator analyzer based on ISO/IEC 25022 standards and found that web-based systems could improve monitoring and management (Servile et al., 2023). Ekha Rifki Fauzi et al. developed an IoT-enabled electric baby warmer for hypothermia risk reduction, which illustrates the integration of real-time monitoring and control (Fauzi et al., 2023). In the meantime, Syaifudin et al. stressed routine maintenance and technological replacement for infant incubators to work without any disruption in health facilities (Syaifudin et al., 2023). Regardless of the progress, the problem remains regarding trade-offs between cost, functionality, and accessibility. In high-performance equipment such as the Giraffe Omnibed®, have added functionalities, yet are too costly for most LMICs. On the other hand, cheaper alternatives such as the Embrace Nest present less expensive options, but they may not have the following features of a real-time monitoring IoT-based solutions and AI-based technology that can provide adaptive temperature and humidity, such as the NeoSmart Crib, are energy dependent and difficult to scale. Solar-powered prototypes and 3D-printed designs have emerged as some of the most promising, but struggle in terms of durability and sterilization concerns. Current research is leaning toward hybrid solutions, such as incubators paired to provide temperature, humidity, and ventilatory control, and distributed manufacturing to increase accessibility. Although current systems achieve excellent accuracy, trade-offs between portability, advanced function, and cost need still to be addressed in the future for low-resource regions where rate of neonatal mortality is still unacceptably high. From the ethical point of view, emphasized by McCord, it will be essential to keep considering ethical principles in any rates of these technologies, to assure that advances in neonatal care are effective and fair.

Research Methodology

The “IncuSense” baby incubator prototype is powered by an ESP32 as the central control unit, integrating DHT22 sensors for temperature and humidity monitoring, and MAX30100 sensors for tracking SpO2 and heart rate. Real-time data is displayed on an LCD screen. The system includes a PTC heater fan for consistent temperature control and a servo-based actuator to regulate oxygen levels, ensuring optimal conditions for the baby’s well-being. Figure 3, designed and developed by our team, refers to the working of modality. The system initially displays the ambient conditions, including temperature and humidity. Preset values for optimal temperature, humidity, and oxygen saturation are input into the system. It continuously adjusts the environment using a regulation mechanism that includes a PTC heater fan, active humidifiers, and a servo-based actuator connected to the oxygen cylinder until optimal conditions are reached. The PTC heater fan activates if the temperature deviates, and the humidifier operates similarly. Oxygen levels are regulated by monitoring blood oxygen saturation; if saturation is too high, the actuator reduces the oxygen flow from the cylinder, and if too low, it increases the flow. Once the target conditions are achieved, the system stops the regulation process and continues to monitor and display the parameters.

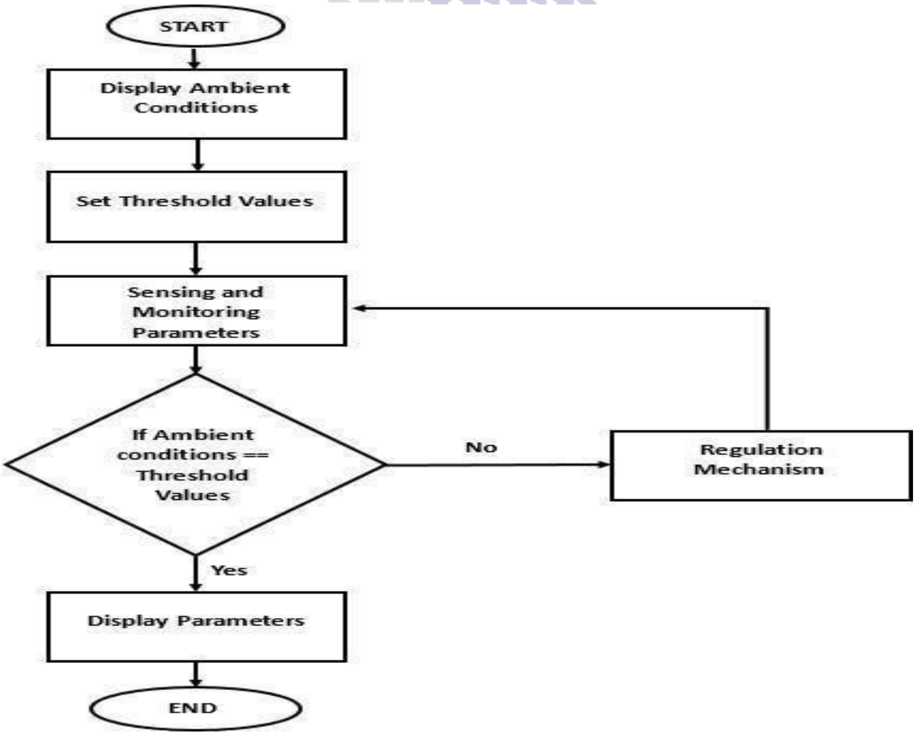

Figure 3 Flow Diagram of Incusense

Results and Discussion

Baby incubators are critical care devices that provide a controlled environment for premature babies. This research effort presents the “IncuSense”, new incubator prototype that combining a servo-based oxygen flow control actuator and a sensor-driven system for temperature and humidity regulation. This concept leverages the precision and responsiveness of servo motors and sensors to provide a more dynamic and flexible environment for premature babies, helping in their proper growth and development. The advancement of this prototype baby incubator to control servo-based oxygen flow through actuator and sensor-driven system for temperature and humidity, create a stable environment. As show in Fig. 4, which we specifically designed for this study. The transparent acrylic chamber allows continuous monitoring, while circular access ports and an integrated control panel facilitate accurate adjustments or care and the design holds potential for clinical application, offering significant improvements in neonatal healthcare and supporting better outcomes for premature babies.

Figure 4 IncuSense: 3D Design and Functional Prototype

Temperature and Humidity Regulation Measurement

When the system is turned on and the temperature is set to the predetermined value, it takes 15 minutes for the ambient temperature to reach the desired value during the experiment startup. This initial heating phase is crucial, as it ensures that all measurements taken during the experiment are accurate and reliable. Once the target temperature is achieved, the system can maintain stability for the duration of the experiment. The system compares the user-defined temperature and humidity values with the actual measurements and then adjusts to maintain the specified ranges. Table 1 shows the user-defined pre-set temperature values alongside the measured values recorded by a digital hygrometer, which also serves as a validation tool. This process is similarly applied to humidity levels, as shown in Table 2. The data demonstrates that the system effectively reaches the target conditions and successfully maintains the desired ranges. During the design process, standard simulation techniques were employed to assess the project's reliability, with consultation from a medical expert to review and validate the simulation parameters. The prototype was 881igoroussly evaluated through clinical trials conducted at a local hospital, where live test subjects were involved to assess its performance and safety.

Table 1 Temperature Regulation Mechanism Performance

Pre-set Temperature(°C)	Measured Temperature(°C)	Error	Time Taken
29	28.7	0.3	15 min
31	31.2	0.2	19 min
33	32.9	0.5	25 min
35	35.2	0.2	31 min
37	36.5	0.5	34 min

Table 2 Humidity Regulation Mechanism Performance

Pre-set Temperature(°C)	Pre-set Humidity (%)	Measured Humidity (%)	Error (%)
29C	40%	40%	0%
31C	42%	41.50%	0.50%
33C	45%	45.50%	0.50%
35C	50%	55.50%	0.50%
37C	55.50%	60%	0.50%

Oxygen Regulation Measurement

Since this prototype also includes an oxygen regulation mechanism, precise control is crucial. However, as it is still a prototype, it is not yet suitable for clinical trials. To validate its functionality, the system was tested using OxSim1, a simulator for SpO2. First, the minimum and maximum saturation ranges were input into the system. The OxSim1 was then connected to the sensor to provide feedback. As the SpO2 levels fluctuated, the system adjusted the oxygen flow using the actuator. The results, demonstrated in Table 3, indicate that the system performs well, showing promising effectiveness in oxygen regulation.

Table 3 Oxygen Regulation Mechanism Performance

Preset Saturation Values (%)	Preset Oxygen flow(L/min)	Measured Flow(L/min)	Measured Saturation (%)
85-94	5	4	93.3
89-95	2	1.8	94
92-97	1	0.7	94.5
95-98	1	0.7	97
98-99	0.5	0.2	98

Figure 5, created by our team, depicts the conclusive design of our prototype.

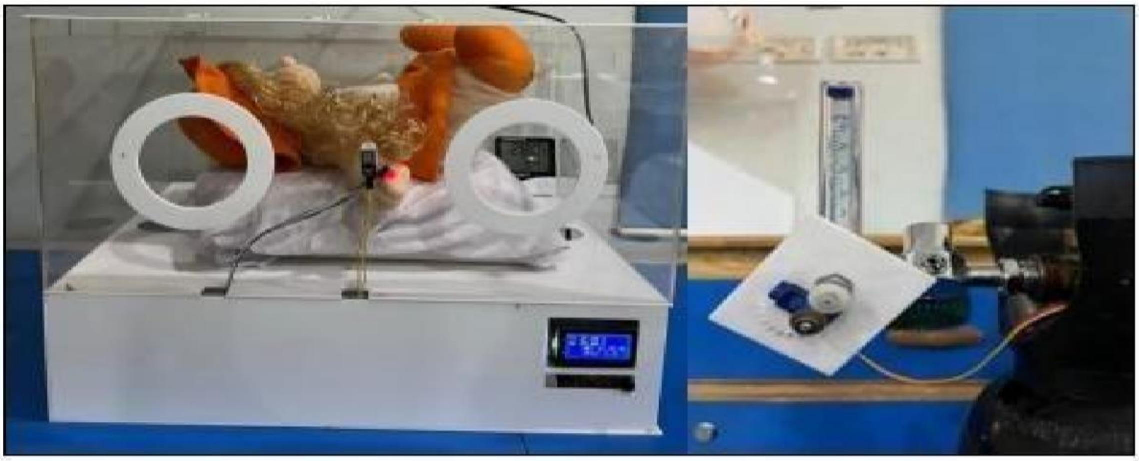

Figure 5: 3D design and Functional Prototype

Conclusion and Future Work

The primary aim was to design and implement an efficient system for controlling the temperature and humidity of baby incubators, integrated with a mechanism to regulate oxygen flow provided to Babies. The study's findings demonstrate that the system accurately maintained the desired temperature with a deviation of only 0.3-0.5°C, **regulated humidity within 0.5-1%, and controlled oxygen flow with deviations ranging from 0.2-1 L/min, all while adhering to the preset oxygen saturation ranges.** This consistency demonstrates the incubator's strong ability to regulate temperature and humidity, resulting in a stable environment for neonatal care. Validation using a digital hygrometer and OxSim1 simulator confirms the system's potential for reliable environmental control in incubators. Future work will involve refining the prototype for enhanced reliability and performance, particularly in oxygen regulation, with the ultimate aim of preparing it for clinical trials.

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