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Design of smart baby incubator for low-birth-weight newborns

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ABSTRACT

The neonatal mortality rate in Indonesia remains high, with 15 deaths per 1000 live births, exceeding the target of below 10 per 1000 live births. One significant cause is Low Birth Weight (LBW), often resulting in fatalities. Baby incubators are essential for LBW management, but conventional incubators rely on manual monitoring, requiring continuous nurse presence to maintain stable incubator conditions. Previous studies have introduced smart incubator systems; however, most focus solely on monitoring room conditions without considering the baby's health status. This research aims to develop a smart baby incubator capable of real-time monitoring of both incubator room conditions (temperature, humidity, and oxygen levels) and baby conditions (body temperature, heart rate, oxygen saturation, crying detection, and visual observation). By integrating Internet of Things (IoT) technology, the system provides comprehensive monitoring to enhance the quality of neonatal care. The proposed smart incubator monitors the highest number of parameters compared to existing systems, addressing critical gaps in neonatal health management and improving the reliability of care for low-birth-weight infants.

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1. INTRODUCTION (10 PT)

Based on data released by the Central Statistics Agency (BPS), the Indonesian nation will experience a peak demographic bonus period between 2020 – 2035 [1]. This demographic bonus is interpreted as an opportunity for the Indonesian nation to maximize achievements in the country's development efforts. The large number of productive-age population can provide a source of labor and economic actors who play an important role in accelerating development achievements in 2045 [2]. However, in order to achieve this demographic bonus, it is necessary to have good supporting demographic conditions [3]. One of the classic problems of demography in Indonesia is the still high infant mortality rate. Based on health profile data in 2017, it is known that the infant mortality rate in Indonesia is still quite high. This is indicated by the neonatal mortality rate (NAR) which is 15 per 1000 live births, where the target achieved by Indonesia should be below 10 per 1000 live births [4].

The high infant mortality rate can be caused by cases of babies born with Low Birth Weight or in Indonesians called “Berat Badan Lahir Rendah” (BBLR), where BBLR is defined as a condition where a newborn baby weighs less than 2500 grams [5], [6]. This condition causes unstable body temperature, respiratory problems, digestive and nutritional disorders, and other disorders that can be fatal for babies [7], [8], [9]. The usual treatment is to maintain the environmental temperature to keep it warm, provide good oxygenation procedures, and intensively observe vital signs [10].

One form of intensive care for BBLR babies is to use a tool commonly called a Baby incubator. A baby incubator is a tool that provides a closed place to put a baby, has a controlled environment for medical care [11], and protect the baby from possible infections [12]. Behind the usefulness of this device, there are still major shortcomings in terms of implementing monitoring on each existing baby incubator [13]. This condition can occur when nurses must always monitor each incubator one by one, so that the service cannot run efficiently. Another disadvantage is the need for the presence of nurses around the baby incubator to ensure that the condition of the baby incubator room is still stable or not [14]. These disadvantages have a negative impact on the handling of existing cases of BBLR babies, which further increases the possibility of death of BBLR babies.

Several studies have been conducted to address the shortcomings of the baby incubator, resulting in a system commonly known as a smart incubator. Several studies have been conducted to address the shortcomings of traditional baby incubators, leading to the development of smart incubators. For instance, research by [15], [16] implemented a monitoring system for incubator room conditions using Internet of Things (IoT) technology, focusing on real-time detection of room temperature and its changes. In both systems, it was determined that the room temperature that must be maintained is 33°C - 35°C. This system transmits alerts to healthcare providers via web messages or activates a buzzer when abnormal conditions occur. Another study [17] developed a smart incubator equipped with temperature control, humidity regulation (40% - 60%), and lighting intensity adjustment, ensuring these parameters remain within optimal ranges that mimic the mother’s womb. Similarly, [18] enhanced the system by integrating a more comprehensive monitoring system for temperature and humidity, combined with automated controls for maintaining ideal conditions. Furthermore, all that research [15], [16], [17], [18], [19] explored the application of IoT-based technologies for remote monitoring and control, enabling healthcare professionals to monitor incubator conditions from a distance. These studies collectively highlight advancements in smart incubator technology, focusing on improving neonatal care through enhanced monitoring and automated control of environmental parameters.

Based on the research mentioned earlier, most of the current smart incubator developments are only focused on knowing the condition of the incubator room, but only a few observe the effect of changes in the room's conditions on the baby's condition [16]. Therefore, we developed a smart incubator system design that has a more comprehensive monitoring system for the baby's condition and the condition of the incubator room. The design developed will utilize 6 types of sensors, namely temperature sensors, humidity sensors, oxygen concentration sensors, heart rate sensors, sound sensors, and visual sensors. Each sensor will be used to monitor the temperature, humidity, and oxygen levels in the incubator room. In addition, this smart baby incubator can also monitor the baby's temperature, heart rate and oxygen concentration, baby's crying, and baby's visual condition. The results of the monitoring will then be delivered to users in real-time with the Internet of Things (IoT) system so that they can be observed on each user's device.

2. METHOD

This section will explain how the research implementation method is carried out. This research was conducted experimentally by making a smart baby incubator prototype equipped with an 8-parameter monitoring system (baby and room temperature parameters, room humidity parameters, room oxygen concentration parameters, baby oxygen saturation, baby heart rate parameters, baby cry sound parameters, and baby visual parameters) in real time using IoT technology. This research will have independent variables in the form of the application and integration of temperature sensors, humidity sensors, oxygen concentration sensors, heart rate sensors, sound sensors, and visual sensors in the baby incubator. While the dependent variables are the results of monitoring changes in room and baby temperature values, room humidity, baby oxygen concentration, baby heart rate, recording baby crying sounds, and recording baby activities visually. The flow of this research will be illustrated through the flow diagram in Figure 1 below.

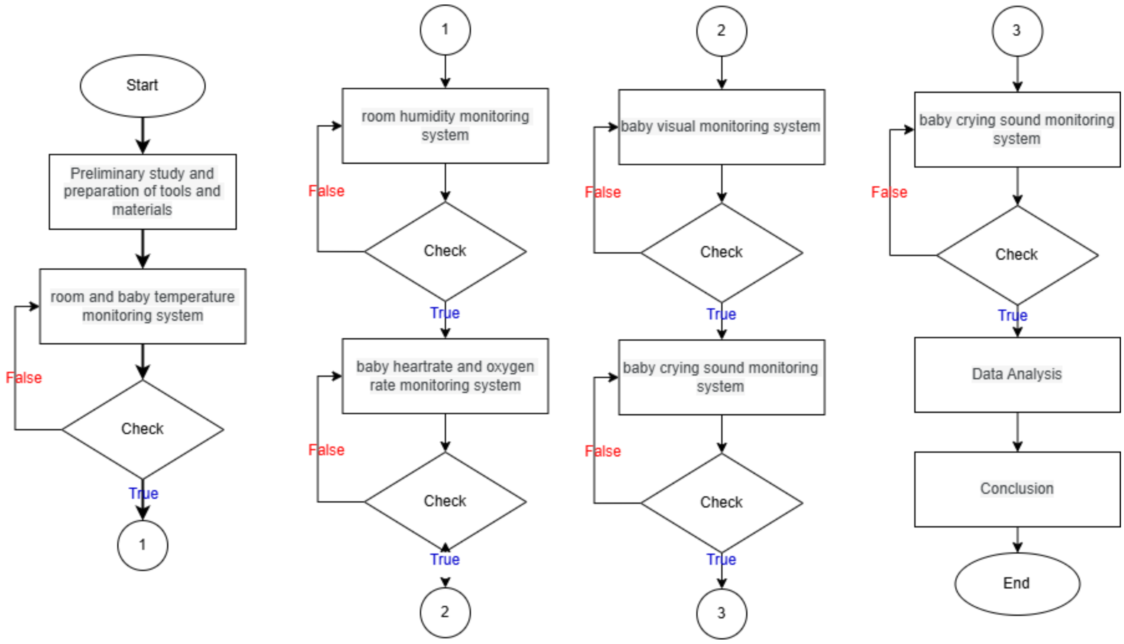


Figure 1. Flowchart of the research

2.1 Preliminary Study and Preparation of Tools and Materials

The research activity will begin with a preliminary study stage, which aims to determine the conditions and influence of the baby incubator room that can support the development of BBLR babies, and how the development of research on smart baby incubator technology. In addition, the output of other preliminary study stages is an understanding of the concept of the sensor that will be used along with the parameters that will be monitored. The next stage is the preparation stage of tools and materials, where the tools and materials needed in general are as follows:

a) Standard baby incubator (does not have an automatic monitoring and control system) which only has an incubator room and a heating room that has a thermostat-based temperature setting;
b) ESP 8266-based microcontroller (NodeMcu 8266 v3) which is used for data processing and Internet of Things-based communication where in its preparation it requires 2 of these micros due to data communication constraints between one sensor and another;
c) Non-contact temperature sensor (MLX90614) to measure the surface temperature of the baby, room temperature and humidity sensors (DHT22);
d) Heart Rate and SPO_2 sensors (I2C O_2 OXYGEN and MAX30100) which are used to measure the baby's heart rate, oxygen saturation, and measure oxygen levels in the incubator room;
e) Sound sensor (Microphone sound sensor module) which is used to detect the baby's cry;
f) Visual sensor (ESP32 CAM) used to display images or videos of conditions inside the incubator room.
g) Supporting tools and materials for installing a monitoring system on a standard baby incubator (such as: cables and connectors, a 5V Universal adapter, solder and tin, adhesives, component protection boxes, and so on)

2.2 Prototype Making Stages

This stage is done by creating a tool design that will be realized in this study. The design is poured into the tool diagram as follows.

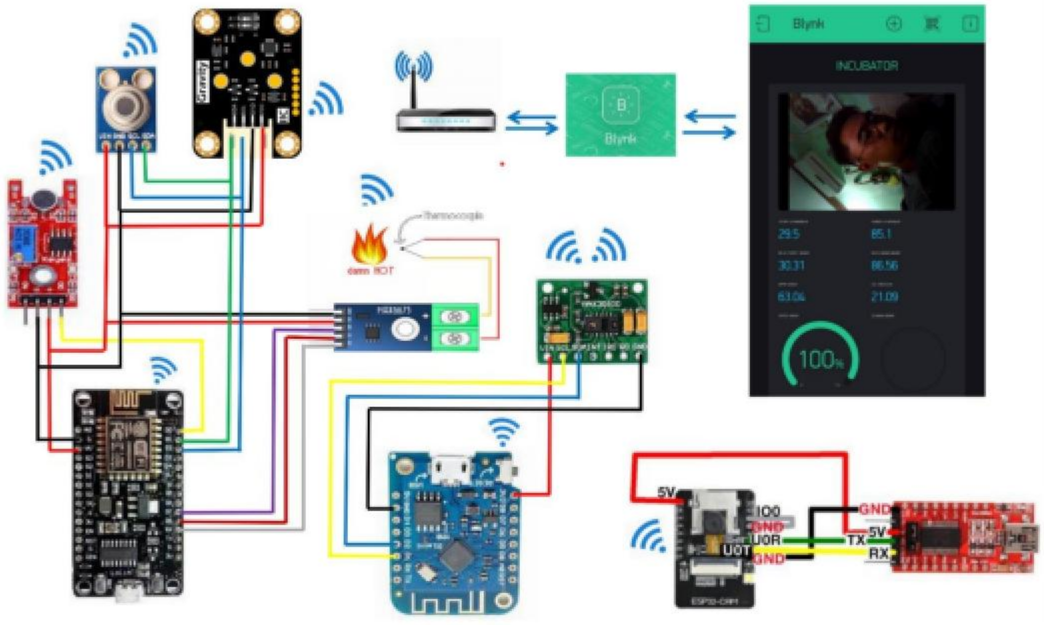


Figure 2. Diagram of the monitoring system in the smart baby incubator

Based on the block diagram in Figure 2, the tool that is designed will attempt to integrate the monitoring system that comes from the output of the 6 types of sensors that have been mentioned previously [13], [16], [20]. In the process of compiling each monitoring system will be compiled one by one based on the parameters to be observed, for example in the first stage of making a prototype is to create a baby temperature change monitoring system using a non-contact sensor connected to a microcontroller to process the output data from the sensor. After the microcontroller has successfully processed the output data, it will be checked by comparing its value using an existing temperature measuring instrument such as a body thermometer or *thermogun*. The stages of making this monitoring system prototype will be repeated until all the parameters to be monitored have been successfully processed by the microcontroller and can be displayed in real time using IoT based on the diagram in Figure 2.

This integrated monitoring system will then be assembled in such a way that it can become a smart baby incubator. To test the precision and durability of the Smart baby incubator technology that has been developed, testing is carried out by comparing the sensor reading values with the reading values of the calibrated tool. Testing is carried out by finding the % difference between the sensor reading data and the reading data of the calibrated tool with the following equation:

$$\%\,Difference = \frac{|A - B|}{B} \times 100\%$$

This equation shows that the % difference is obtained from the difference between the sensor reading on the tool (A) - the reading from the calibrated tool (B) divided by the reading value of the calibrated tool (B). Because this research is still in the form of initial research (pilot), further testing to measure parameters in the baby's body such as heart rate, oxygen concentration, crying intensity, and visual changes in babies cannot yet be tested directly on LBW babies who are very vulnerable to the interventions given to them. In addition, due to the limitations of the calibrated test equipment available, the data that can be compared is only the temperature sensor reading data on the equipment compared to the readings from the calibrated *thermogun*.

3. RESULTS AND DISCUSSIONS

This section will discuss the results of each sensor, the user interface (UI) display of the smart baby incubator system developed, as well as the test values of body temperature measurements with the DHT22 sensor. The purpose of this test is to determine the level of precision and resilience of the system that has been developed. However, this study has not been able to conduct further testing for measuring parameters in the baby's body such as heart rate, oxygen concentration, crying intensity, and visual changes in the baby because the system developed is still in the early research stage so it cannot be tested directly on BBLR babies who are very vulnerable to the intervention given to them.

3.1 Digital Humidity Temperature Sensor

In this smart baby incubator system, the DTH22 sensor is used as an input to read the temperature and humidity of the incubator room. In testing, the DHT22 sensor is placed in the baby incubator room to obtain information on the temperature and humidity in the baby incubator room. Testing is done by reading the temperature with a value of 40˚C. The results of the DHT22 sensor test can be seen in Figure 3 below.

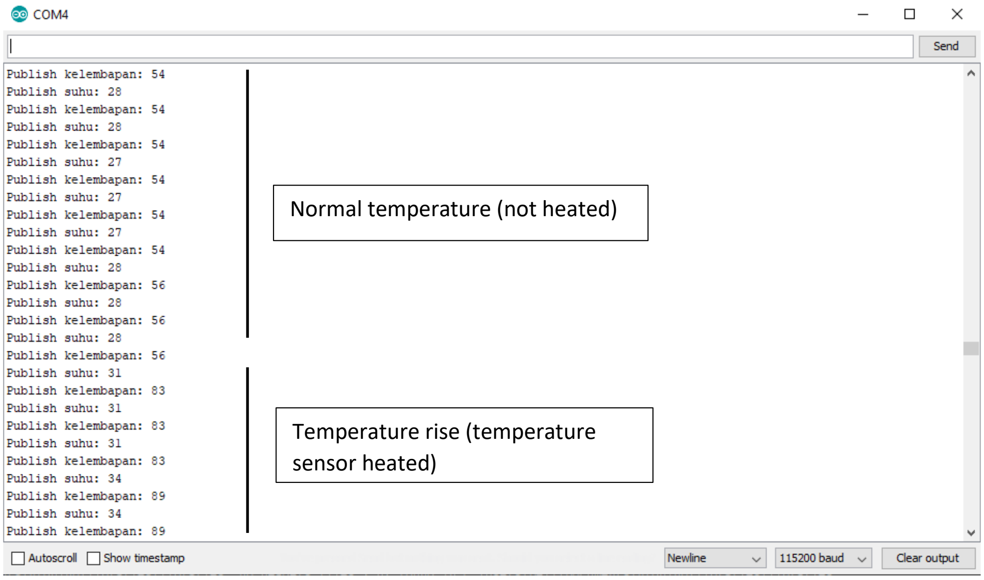


Figure 3 The results from DHT22 sensor

As validation of the sensor reading, a comparison is made between the DHT22 sensor reading value and the thermogun reading value. From this comparison, it can be concluded that the average of difference percentage value of the two is 1,42 %. For more details, it will be displayed in table 1 below

Table 1 Comparison of Temperature Values between DHT22 and Thermogun

No	DHT22 Temperature Value (°C)	Thermogun Temperature Value (°C)	% Difference
1	37	37,2	1,23%
2	38	38,9	2,43%
3	39	39,8	1,38%
4	39	39,8	1,48%
5	41	40,9	0,84%
6	41	41,2	1,71%
7	41	41,2	1,77%
8	42	42,2	1,10%
9	42	41,9	0,19%
10	42	42,7	2,07%
Avg.	40	40,6	1,42%

3.2 Non-Contact Temperature Sensor

In this smart baby incubator system, the MLX90614 sensor is used as an input to read the body temperature of BBLR babies. In its application, the MLX90614 sensor will be placed in the incubator room and brought close to the baby's location. The reading results from the MLX90614 sensor can be seen in Figure 4 below.

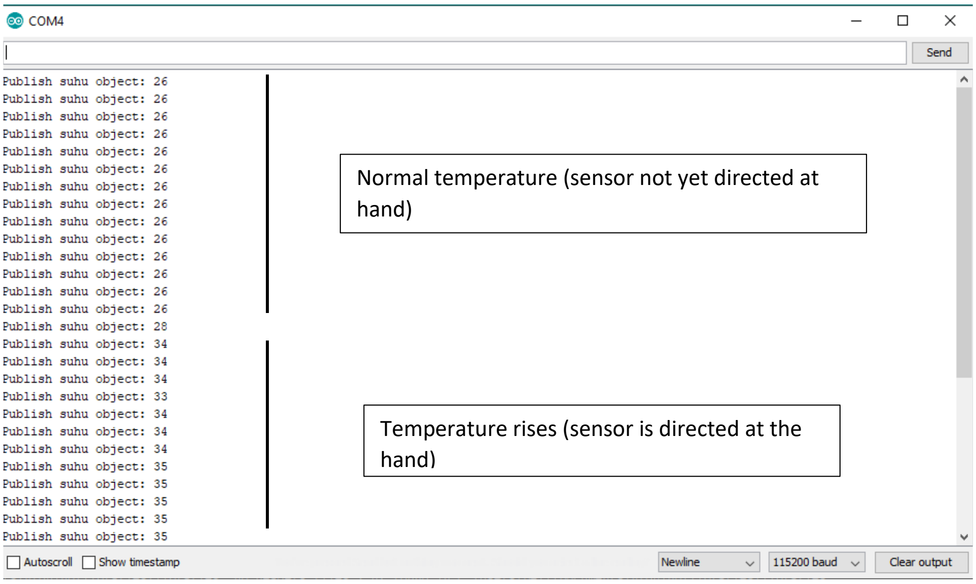


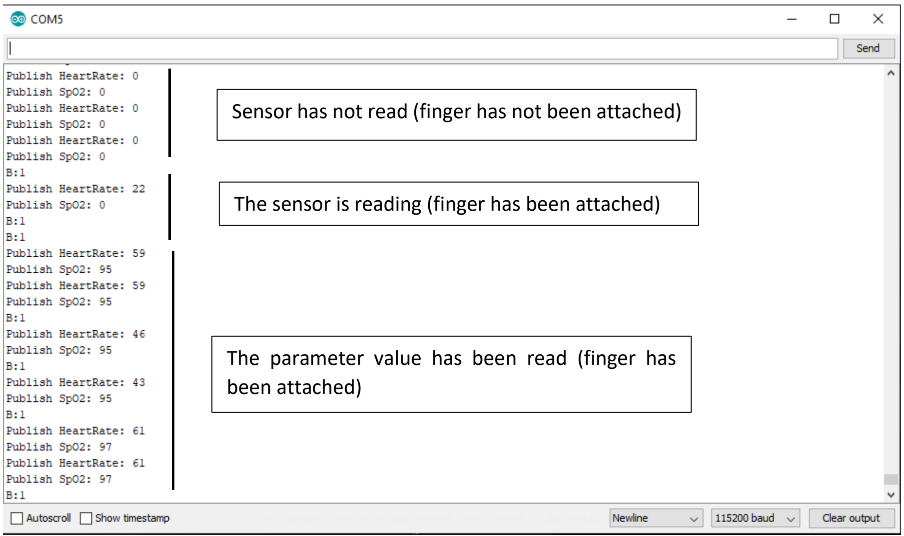
Figure 4 The results from MLX90614 sensor

Based on the Figure 4, it can be seen that this non-contact sensor will always read the temperature around it. Therefore, this sensor needs to be placed close to the surface of the baby's skin, especially in parts that are easy to measure the temperature. The validation process for this MLX90614 sensor has not been confirmed because the device developed has not been tested directly on BBLR babies.

3.3 Heart Rate, SPO$_2$, and Oxygen Concentration Sensor

For measuring the heart rate and SPO$_2$ of the baby, the I2C O_2 OXYGEN and MAX30100 sensors are used. Where the I2C O_2 OXYGEN sensor plays a role in reading the oxygen concentration of the incubator room, while the MAX30100 sensor is used to measure the heart rate and oxygen saturation in the blood of BBLR babies. The I2C O_2 OXYGEN sensor is placed on the wall of the incubator room, this sensor requires time to initialize for 3 - 5 seconds. Therefore, according to Figure 5 (b) it can be seen that the sensor has an initial value of 0 and increases over time. While the MAX30100 This sensor will capture the light intensity value due to changes in heart rate and oxygen saturation. This sensor can work well if placed correctly on the tip of the baby's finger as exemplified in figure 5 (a). The reading results from the MLX90614 and I2C O_2 OXYGEN sensor can be seen in Figure 5 below.

(a)



(b)

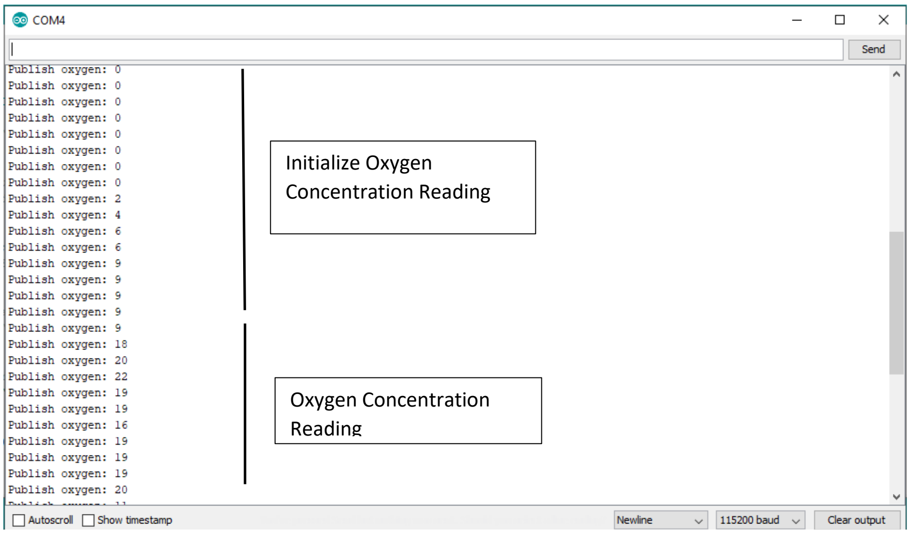


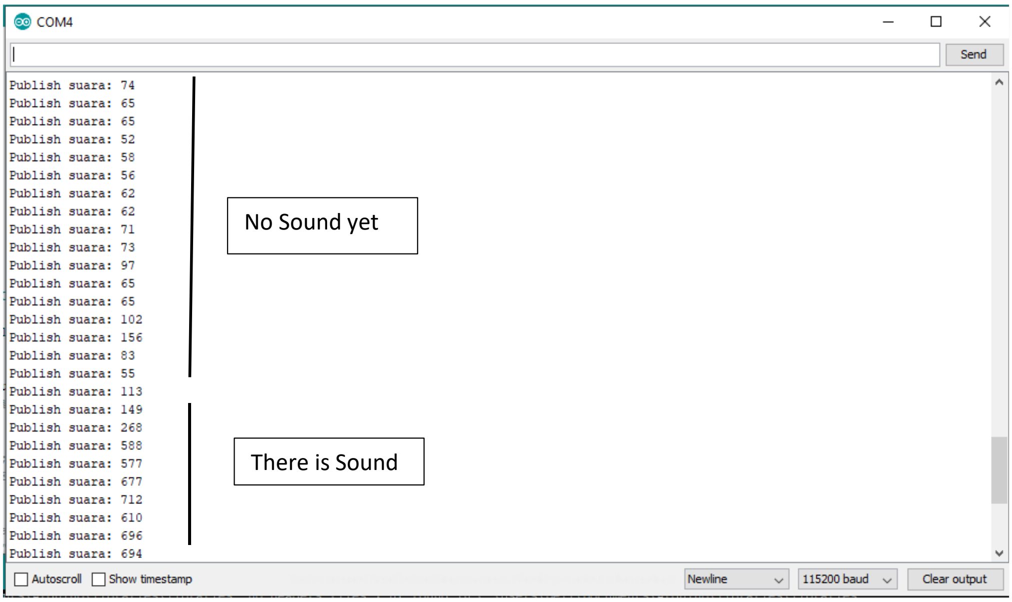
Figure 5 Parameter results from the sensors: (a) MAX30100, and (b) I2C O2 OXYGEN

The validation process for the I2C O_2 OXYGEN sensor reading has not been carried out due to the limited calibrated test equipment to compare the sensor reading values. While the validation of the MAX30100 sensor has not been confirmed because the tool developed has not been tested directly on BBLR babies.

3.4 Baby Cry Sound Sensor

In this smart baby incubator system, a Microphone Sound Sensor Module (MSSM) sensor is used as an input to read the sound of a baby's cry. The baby's cries captured by this sensor still cannot be directly displayed on the user interface of the system being developed, it can only be displayed in the form of serial data as shown in the Figure 6(a). Because of this, the data is changed into the form of sound intensity which can make it easier for users to observe it visually as shown in the Figure 6(b). The reading results from the MSSM sensor can be seen in Figure 6 below.

(a)



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(b)

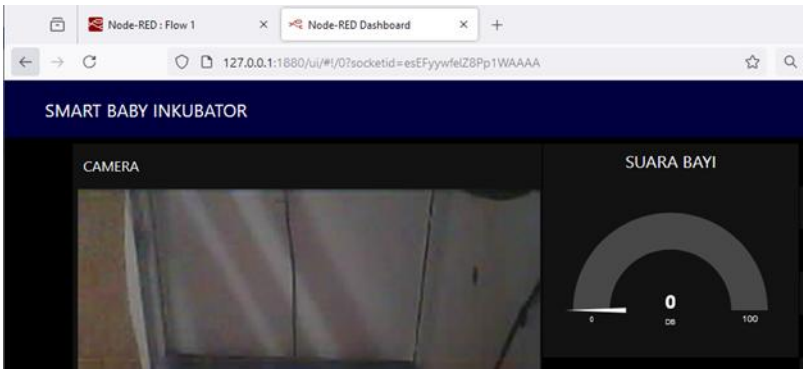

Figure 6 Capture results from MSSM: (a) serial data monitor, and (b) intensity of baby's cry meter

The validation process for reading the sound sensor has not been able to be carried out due to the limitations of calibrated test equipment to compare the sensor reading values. In addition, at this time the sound captured by the sound sensor cannot distinguish which sound comes from the baby and which sound comes from the outside environment.

3.5 Visual Sensor

The smart baby incubator developed uses an ESP32 CAM sensor that acts as an input to read the baby's movement or activity in the incubator room. The reading results from the ESP32 CAM sensor can be seen in Figure 7 below

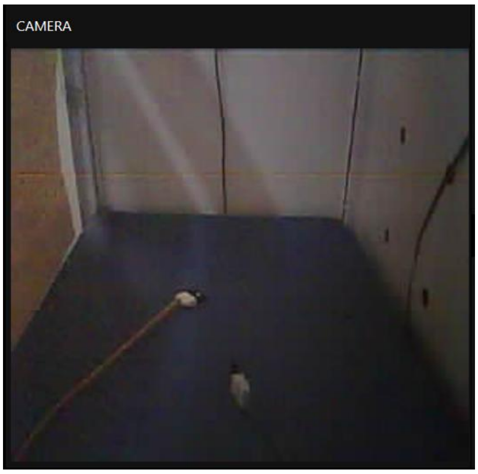

Figure 7 Capture results from ESP32 CAM

The results of the ESP32 CAM sensor reading are still not clearly visible because the resolution of the camera is still very low. The results of all the parameters monitoring will then be displayed further in the UI of this Smart Baby Incubator. The UI allows users to access the condition of the incubator room and the condition of the baby in real time using IoT technology as shown in the Figure 8 below.

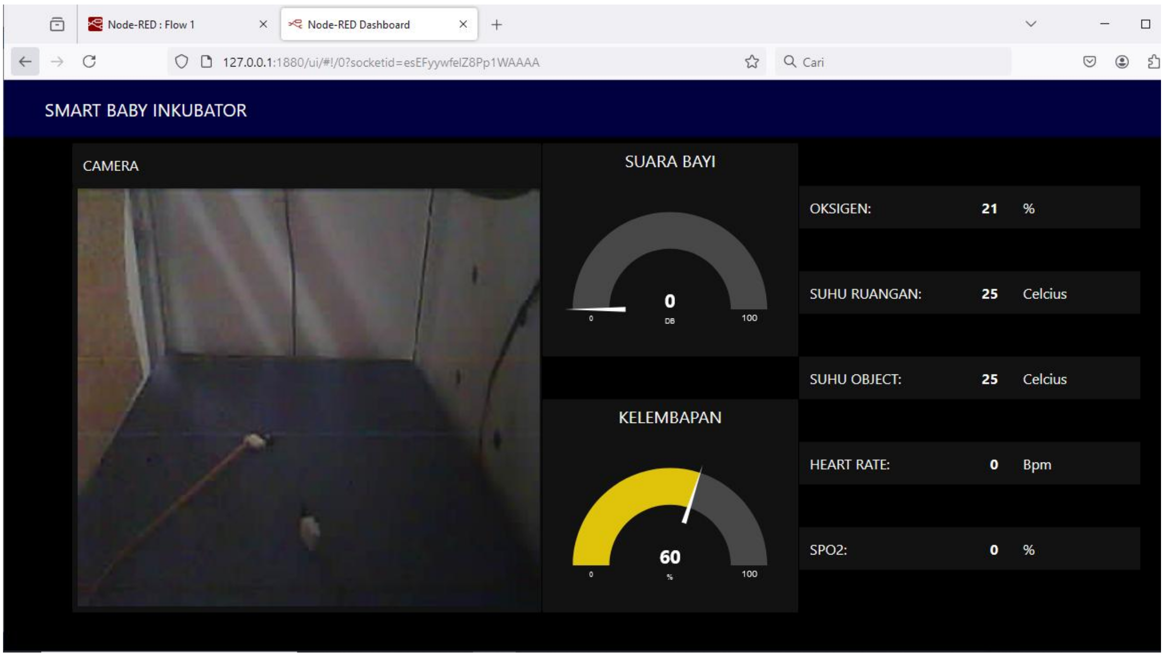

Figure 8 Smart baby incubator UI

All of these results were then compared with the previous research as shown in the following table 2.

Table 2 *Comparison of Number of Parameters*

No.	Ref. No.	Developed Technology Name	Number of Parameters		
			Incubator Room	Baby Condition	Control System
1	[16]	Intelligent Baby Incubator	1	1	1
2	[17]	Smart Baby Incubator	2	2	2
3	[18]	Monitoring and Control System of Infant Incubator	2	1	1
4	Proposed Method	Smart Baby Incubator for Low-Birth-Weight Newborns	3	5	0

Based on Table 2, it can be observed that the developed Smart Baby Incubator outperforms previous studies in terms of the number of monitored parameters. This study successfully integrates real-time monitoring for both room conditions (temperature, humidity, and oxygen levels) and baby's conditions (body temperature, heart rate, oxygen saturation, crying detection, and visual monitoring). In contrast, the reference study [17] primarily focuses on temperature and humidity control of the incubator room, making it the most advanced in terms of control capabilities. However, this study specifically addresses the gap where previous research lacked real-time integration for monitoring the baby's physiological conditions comprehensively. Although the current study does not yet include an automated control system for room conditions, it lays the groundwork for further development. By focusing on adding real-time monitoring to affordable, widely available incubators, this research provides a cost-effective solution for neonatal care, particularly in resource-limited settings.

Future work will emphasize integrating smart control mechanisms to optimize room parameters, ensuring better stability for both baby and incubator conditions.

4. CONCLUSION

Based on the results and discussions obtained from this study, it can be concluded that this study has succeeded in producing a Smart Baby Incubator for Low-Birth-Weight Newborns. This incubator has the ability to monitor in real time 3 parameters of the incubator room conditions, namely: temperature, humidity, oxygen levels. In addition, this incubator can also monitor in real time 5 parameters of the baby's condition, namely: body temperature, blood oxygen saturation, heart rate, baby's crying sound, and visual changes in the baby. The real-time data transmission by IoT system allows healthcare providers to continuously monitor and respond promptly to changes in incubator conditions. Compared to conventional systems, this technology offers the capability to minimize manual monitoring errors and optimize clinical interventions through automated data acquisition and analysis. It is hoped that in the future this study can be a reference study to develop a Smart Baby Incubator that can be used and tested on BBLR babies directly. In addition, future research will focus on improving sensor accuracy, expanding system functions, and including predictive features to detect abnormal conditions earlier. These advances are expected to further improve the reliability of this technology in clinical practice and reduce the number of BBLR baby deaths in Indonesia.

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CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Author1: Conceptualization, Methodology, Software, Project administration, Writing – original draft. **Author2**: Conceptualization, Methodology, Software, Writing – review & editing. **Author3**: Conceptualization, Validation. **Author4**: Conceptualization, Software, Writing – original draft**.**

DECLARATION OF COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data will be made available on request.

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