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Design of Infant Incubator Analyzer

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ABSTRACT

Approximately 80% of newborn babies are placed in incubators in Turkey. In the incubator, the mother's uterus is simulated and the vital parameters of the newborns are maintained. The incubator provides a noiseless environment for babies with suitable temperatures and humidity. The complete functioning of the incubator is possible only if the incubators are kept under control by preventive maintenance. The purpose of this study is to design and develop a reliable incubator analyzer that ensures the sustainability of incubators. This study presents a detailed design of an analyzer that can be used to monitor the functional parameters of the incubator by means of three different sensors controlled by an AVR Atmega32 microcontroller unit and interfaced with a liquid-crystal display. In the analyzer, temperature, humidity, and noise measurements have been targeted. DHT11 sensor performed quite well with an average error ratio of 3.54% for air temperature measurements and 1.4% for humidity. Mattress temperature sensor (LM35) had an error ratio of 2%. The sound noise sensor was able to detect measurements with an error ratio of ±20 dB. The proposed design is a preliminary prototype that needs further optimization and testing. It is believed that design recommendations generated from this study will form the basis of similar designs in the future.

Index Terms—Infant incubator analyzer, infant incubator maintenance, infant incubator, neonatal intensive care unit, preventive maintenance

I. INTRODUCTION

Each year, about 1 million infants die due to problems that can be prevented by an intensive care unit [1]. Premature and neonatal babies sometimes need extra attention and health care because of their problematic conditions [2]. Congenital anomaly and newborn baby's inability to regulate their body temperature is a leading cause of premature infant death, as well as permanent disability [3-5]. Other factors such as the quality of care during pregnancy and delivery and the immediate care of the newborn play a major role in infant mortality [6]. An important approach to neonatal care is the use of incubators [7], which are baby cribs equipped with a thermal-controlled environment. In addition to these, incubators protect babies from infections, allergies, and harmful noise or light [8]. Therefore, vulnerable newborns, especially premature ones, are placed in incubators providing them with the closest environment to that of the mother's uterus. In these incubators, infants are kept for observation and intensive care by controlling vital parameters such as desirable temperature, humidity, and airflow [9]. Infants are kept in the neonatal intensive care unit (NICU) until the full development of their organs. Infant incubators protect the babies from NICU disturbance and infections. Basically, an infant incubator is a chamber with a mattress covered with a plastic cover. This chamber provides the required environment for infants to be hospitalized [2]. The heater in the incubator is adjusted to maintain the babies' temperature, and a temperature sensor is tapped to the babies' skin to keep the temperature under control [10]. Generally, incubators are used to maintain a stabilized thermoneutral ambient, provision of desired humidity and oxygenation, surveillance for highly sick infants, and isolation of newborn babies from infections and unfavorable external environment [11].

After delivery, neonates must control their body temperature. Normal body temperature is between 37°C and 38°C [12]. In the uterus, babies depend on the mother's core temperature. After birth, they rely on external heat to maintain their core temperature. Their thermal instability exposes them to hypothermia and hyperthermia [13]. and therefore, an infant should be placed in an ideal place post-delivery which is the infant incubator. Careful and continuous surveillance of neonatal babies' temperature increases the survival rate of infants [14].

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Controlling and monitoring neonates' temperature is not enough to protect them from heat loss. In comparison to adults, infants are very sensitive to climate changes because physiologically, they are less effectively adapting to humidity and other weather changes [15]. Neonates, especially premature babies, have underdeveloped skin. Therefore, they are at an increased risk of water evaporation through the skin, leading to temperature instability, dehydration, electrolyte imbalance, and calorie loss [16]. This could be protected by increasing the environment humidity. A study conducted by Hey and Maurice has estimated the effect of relative humidity on normal newborn babies under controlled environmental conditions [17]. This encourages more to use an infant incubator analyzer which will provide the accurate value of humidity within the incubator.

Infants generally are fragile human beings and noise is an important source of stress for them [18]. One of their basic needs is a peaceful environment. In NICU, neonatal babies are exposed to high sound pressure levels (SPL) which disrupts normal growth by hindering the ability to stay in deep sleep [19]. Exposure to excessive noise has been associated with infants' heart rate acceleration, bradycardia, decline in oxygenation, increase in muscle tension, blood and intracranial pressure, sleep disturbance, agitation, and auditory disorders [20]. Reducing sound levels in the NICU has a big and important role to support neonatal development [18].

Preventive maintenance (PM) of infant incubators plays a crucial role in ensuring neonate's safety and survival. Incubators should be inspected and tested, specifically their indicators and sensors, to ensure the efficacy and safety of this device. Preventive maintenance mainly consists of qualitative and quantitative tests. The qualitative test covers the inspection of the equipment, including the line cord, circuit breaker, heater, alarm, and power cord [21]. Considering the vital importance of incubators, they should be kept under continuous tracing, maintenance, and calibration. Although PM is a fundamental safety measure, flaws could occur due to various reasons, especially in qualitative tests which is a critical issue affecting the infants directly [22]. Thus, the incubator's PM should be supplemented with analyzers ensuring that these incubators are operating conveniently and measuring all parameters accurately.

Although the Turkish medical devices industry has developed rapidly within the past decade in most fields [23], no analyzers of infant incubators have been manufactured in Turkey. In this study, we designed an infant incubator analyzer by using unsophisticated electronic components. This prototype incubator analyzer is a preliminary design to be optimized with an ultimate aim to be manufactured by Turkish medical manufacturers in order to supply local medical facilities with an essential maintenance and calibration tool.

II. MATERIALS AND METHODS

As the infant incubator provides the neonates with the appropriate parameters corresponding to their health needs, we needed multiple types of sensors to measure these parameters. The block diagram in Fig. 1 shows the principal parts of the device. All these sensors were interfaced with the AVR microcontroller where analog signals are converted to digital via the Atmega32 built-in Analog-to-digital converter (ADC) unit. The measured parameters were designed to be displayed on a graphical display interfaced with the AVR microcontroller. The parameters of this design were established to ensure portability, efficiency, and easy usage within all kinds of infant incubators.

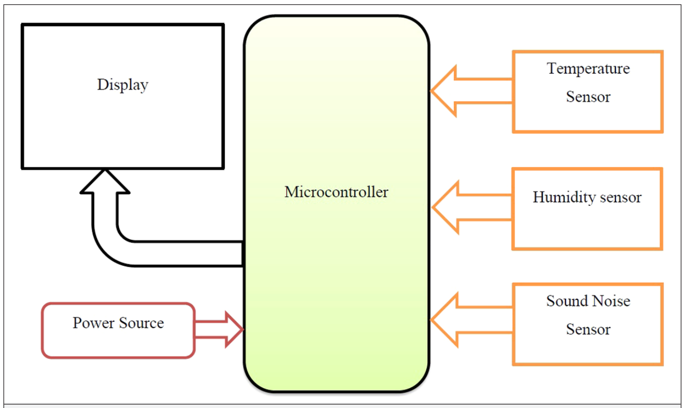

Fig. 1. Infant incubator analyzer design block diagram.

The flowchart in Fig. 2 demonstrates the device operation as follows: after starting the device, the three sensors are initialized. The sensors will start reading and send the data to the Atmega32. The microcontroller converts the signal via the built-in ADC. Then, the results will be displayed on the Graphical Liquid Crystal Display (GLCD).

A. AVR Microcontroller

To deliver a low power consumption and high level of integration, we used AVR Microcontroller unit (MCUs) as they provide a unique combination of performance, power efficiency, and design flexibility. They are also based on the industry's most code-efficient architecture for C programming. The AVR is an 8-bit reduced instruction set computer (RISC) single-chip microcontroller which comes with some standard features such as on-chip code Read-only memory (ROM), data Random Access Memory (RAM), data electrically erasable programmable read-only memory (EEPROM), timers, and I/O

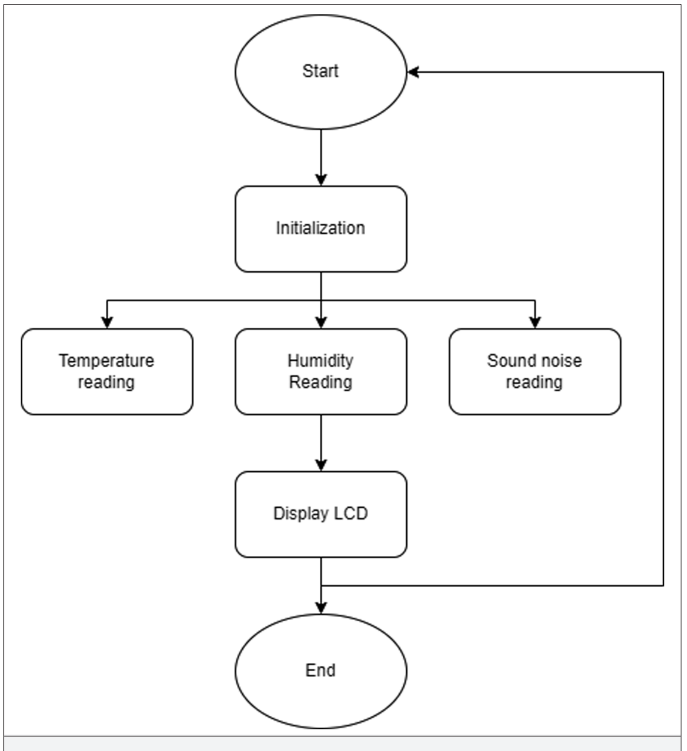

Fig. 2. Infant incubator analyzer flowchart.

ports. In addition, some AVR includes important features like internal Analog to Digital Conversion (ADC), Pulse-width modulation (PWM), Universal Synchronous/Asynchronous Receiver/Transmitter (USART), Serial Peripheral Interface bus (SPI), and Universal Serial Bus (USB) [24]. Due to the importance of the peripherals, we decided to use an AVR MCU, specifically the Amega32 Microcontroller. Atmega32 is an 8-bit AVR RISC based on high performance and low power. It combines 32 kb In-system programming (ISP) flash memory with read-while-write capabilities including 1 kb EEPROM, 2 kb SRAM, 32 I/O lines, three flexible timers, internal and external interrupts, and serial programmable USART, in addition to an 8-channel 10-bit ADC which is the most important feature for our study. This allowed us to interface multiple sensors to the MCU. Currently considering the 8-channel 10-bit resolution feature, the 8-channel implies that there are eight ADC pins located across port A (from PA0 to PA7) and the 10-bit resolution implies that there are 2^{10}= 1024.

In this study, the microcontroller receives input signals through ADC pins PA0 to PA3. In order to process these signals, we had to set the ADC pre-scaler which is determined by the microcontroller clock frequency. Normally, the operation scale of the ADC is somewhere between 50 KHz to 200 KHz. In this study, the ADC frequency was set at 128 kHz. Setting the ADC pre-scaler was implemented through the ADC multiplexer selection register (ADMUX). These bits were used to choose the reference voltage. We also set our reference voltage at Avcc with an external capacitor.

B. LM35 Temperature Sensor

The measurement of temperature is fundamental to ensure infants' safety. There are many sensors that can be employed as medical-grade temperature sensors to help fit a particular application. Typically, Integrated Circuit (IC) sensors are quite ideal for maintaining the temperature at 37°C (normal human body temperature). Therefore, in this study, we decided to use LM35 temperature sensor. The main reason for adopting an IC temperature sensor is its advantage over other sensors calibrated in Kelvin. The LM35 has a linearity proportion to the Celsius (Centigrade) temperature. Moreover, measurements will be more accurate than with a thermistor. The working range of LM35 is from −55°C to 150°C. The LM35 is easy to be included in a measurement application without any elaborate scaling schemes and offset voltage subtraction [25]. Also, it is cost-effective which makes it a good choice for a prototype [1].

LM35 provides a voltage output based on the variation of temperature. As shown in Fig. 3, each +1°C is represented with a +10 mV. Since the output signal from LM35 is analog, it was connected to one of the ADC pins of the microcontroller (PA0). The signal is converted to digital and then the digital value is converted to a centigrade value. Subsequently, we initialized the ADC port by enabling the ADC feature and then started the ADC conversion.

C. DHT11 Humidity/Temperature Sensor

Humidity sensors are one of the most important devices used in biomedical applications for measuring and monitoring humidity. Humidity is a measure of the moisture content in the air and can be measured as absolute humidity or relative humidity. The relative humidity is highly dependent upon air temperature; the higher the temperature the greater the capacity of the air to hold water vapor.

There are multiple types of humidity sensors (hygrometers) such as capacitive, resistive, and thermal conductivity humidity sensor. For the sake of our study, we chose the resistive type, specifically DHT11. It contains a resistive humidity sensor in addition to an Negative Temperature Coefficient (NTC) temperature sensor. DHT11 measures relative humidity. The formula to calculate relative humidity is:

$$RH = p^0 / ps \times 100\%$$

where RH is the relative humidity; p^0 is the density of water vapor; and ps is the density of water vapor at saturation.

This type of humidity sensor is made up of low resistive materials that change significantly with the change in the humidity. This assisted us to obtain our desired accuracy. Basically, this sensor consists of two conductive plates within a non-conductive base. The moisture from the air changes the voltage between the plates.

The built-in NTC negative temperature-coefficient sensor is a variable resistor that changes according to the change in the temperature. It is made of semi-conductive materials compressed to form a temperature-sensitive conducting material. The electrical current flows through the charge carriers within the conductive material. High temperatures cause the semiconducting material to release more charge carriers and that is how the temperature is measured. The values from the sensor are read by the microcontroller and converted into digital values considering the air temperature. DHT11 is a perfect and popular model. It is a cheap, sufficient, and reliable sensor [1]. It also has the ability to be connected to an 8-bit microcontroller. DHT11 digital temperature and humidity sensor is a composite sensor that contains a calibrated digital signal output of the

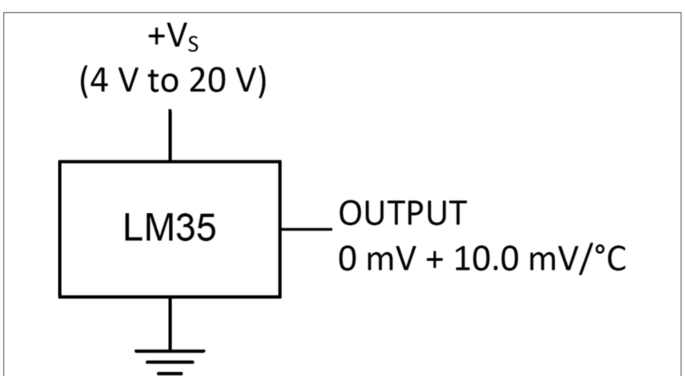

Fig. 3. Centigrade temperature sensor.

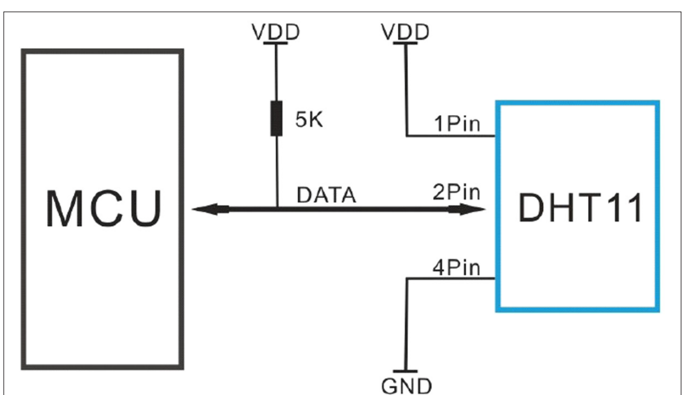

Fig. 4. Typical application of DHT11.

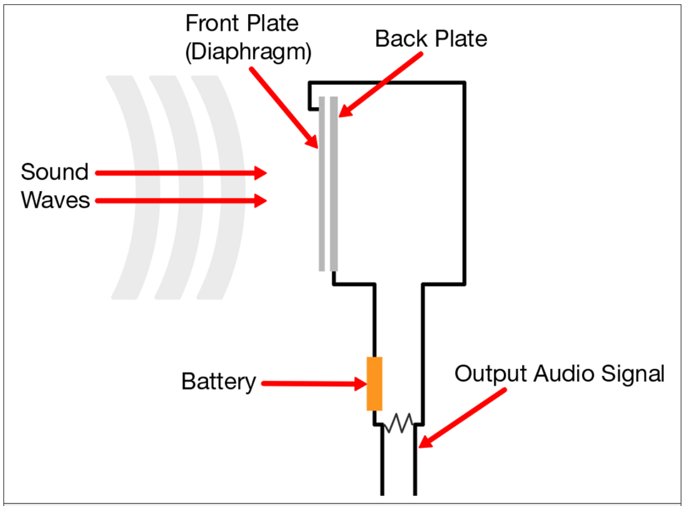

Fig. 5. Condenser microphone diagram.

temperature and humidity [26]. DHT11 uses one line for communication with microcontroller (Fig. 4). Therefore, to start the communication, we need to send a start pulse from the microcontroller to DHT11. That is implemented by pulling down the data pin for about 20 ms and then pulling it up. After implementing the response pulse, DHT11 sends the humidity and temperature values with checksum. The data frame is 5 bytes, 8-bit each. The first two bytes (I RH and A RH) contain the humidity value in decimal which gives the relative humidity value. The next two bytes (I Temp and A Temp) contain the temperature value also in decimal which gives the temperature in Celsius. The last byte contains the checksum which is basically a calculation using the algorithms provided in the programming specifications and communication protocol to determine the data integrity. Once the microcontroller completes receiving the data, DHT11 pin goes low until another start pulse is sent by the microcontroller.

D. Sound Noise Sensor

A sound noise sensor is used to measure sound levels by measuring sound pressure. It is often called as SPL meter. Usually, it is not possible to get an out of box sensor that could measure in decibels. In this study, we designed our own sound noise sensor using a regular DC-based condenser microphone. Condenser microphones are best known for their sensitivity and wide-range frequency. A condenser microphone is constructed of two parallel capacitor plates (Fig. 5). As the sound produces vibrations, the frontal plate (diaphragm) vibrates resulting in a change in the distance between the capacitor plates. This makes a change in the capacitance creating a change in the discharge current.

1) Amplifying the Signal

Unlike temperature and humidity, measuring the sound noise is not a straightforward function. It is necessary to amplify the microphone output signal first to more easily detect it. Usually, the microphone output electrical signals are faint or low, and they would not be

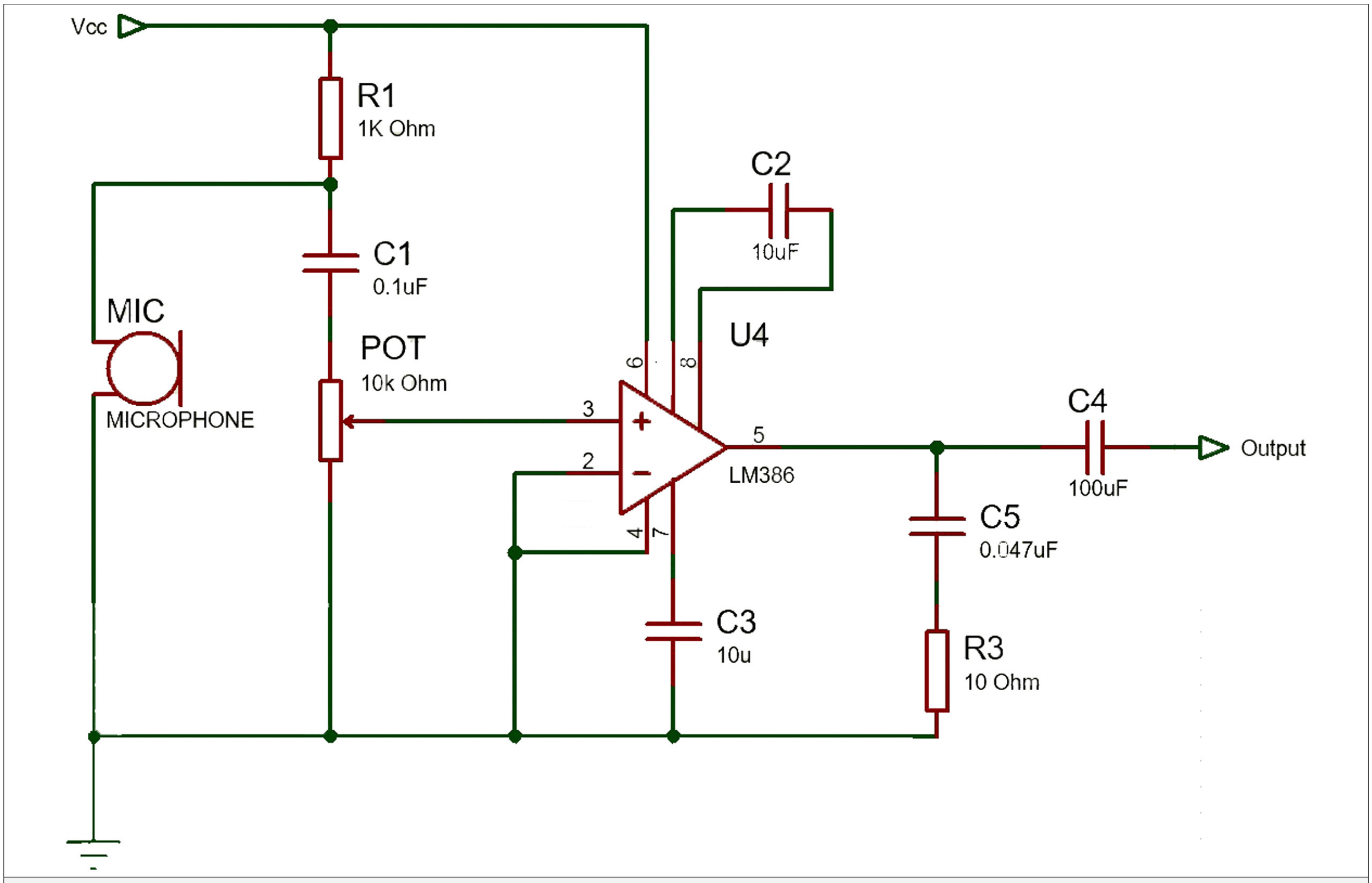

Fig. 6. Schematic representationof the amplification circuit.

detected by the ADC. Therefore, we chose the LM386 low-voltage audio power amplifier. This amplifier gives us a gain from 20 to 200. Terminals 1 and 8 represent the gain control of the amplifier. These are the terminals where the gain can be adjusted by placing a resistor and capacitor or just capacitor between these terminals. In this circuit, we placed a 10_F capacitor between these terminals to obtain the highest voltage gain. Terminals 2 and 3 are the sound input signal terminals. Terminal 4 is ground (GND). Terminal 5 is the output of the amplifier. Terminal 6 is the terminal that receives the positive DC voltage. Terminal 7 is the bypass terminal. This pin is usually left open or is wired to the ground. However, for better stability, a capacitor is added to our circuit as it can prevent oscillations in the amp chip. The schematic for the amplification circuit is shown in Fig. 6.

C1 (0.1 μF): This capacitor is placed to block the DC voltage on the input and and allow only the AC signal, which is the received voice signal. **R1 (1 K Ω):** pull-up resistor determined according to the L-KLS3-MH-HM9767P data sheet. **R2 (10 KΩ POT):** controls the input volume. **C3 (10 μF):** improves the amplifier LM386. **C4 (100 μF):** removes any DC offset from the amplifier LM386 output. **C5 (0.047 μF):** current bank for the output, it discharges whenever there is a current need. The condenser microphone receives the sound signal and converts it into an electrical signal. This signal is amplified by the LM386. It is input to the microcontroller ADC pin to be converted into a digital value.

2) Reading the Signal through the Microcontroller

Once the signal is ready to be read by the microcontroller, it is input into the ADC port in the Atmega32 to be converted to a digital value and then to a decibel value. As we mentioned before, we cannot get a common multiplier or ADC values and decibels. In this study, we have designed our own sound noise sensor, so we are satisfied with an approximate accuracy of decibel values as long as we are designing a preliminary prototype. We used an android application called sound meter as a reference to obtain an equivalent decibel value to the ADC values. Table I shows the equivalent values.

After getting these values, we were able to form the following equation:

$$ADC = (11.005 \times dB) - 83.2075$$

which can be implanted in our programming code in the following equation:

TABLE I. 10 ADC VALUES AND ITS EQUIVALENT IN DECIBEL

dB Value	ADC Value
30	360
35	485
40	410
45	470
50	490
55	500
60	507
62	540
65	600
70	615

$$dB = (ADC + 83.2075)/11.005$$

III. RESULTS

A. LM35 Temperature Sensor

We have implemented a simulation for temperature measurement and its value display on Proteus. We ran our source code through the simulator, and the reading was observed through the liquid-crystal display (LCD). The readings were accurate. The circuit was tested on a board using a 20 × 4 LCD. The source code was burned into the Atmega32 using USBasp. We measured human body temperature by holding the LM35 sensor. A measurement result of temperature of 37°C was observed through the LCD which is the normal human temperature.

B. DHT11 Humidity/Temperature Sensor

DHT11 sensor circuitry has been implemented on Proteus. We ran our source code on the simulator and an accurate reading was observed through the LCD. We implemented the circuit on a testing board using a 20×4 LCD. Then, our source code was burned into the Atmega32. A measurement reading of 56.0% was obtained for humidity and 27°C for temperature knowing that these measurements were taken in a warm room.

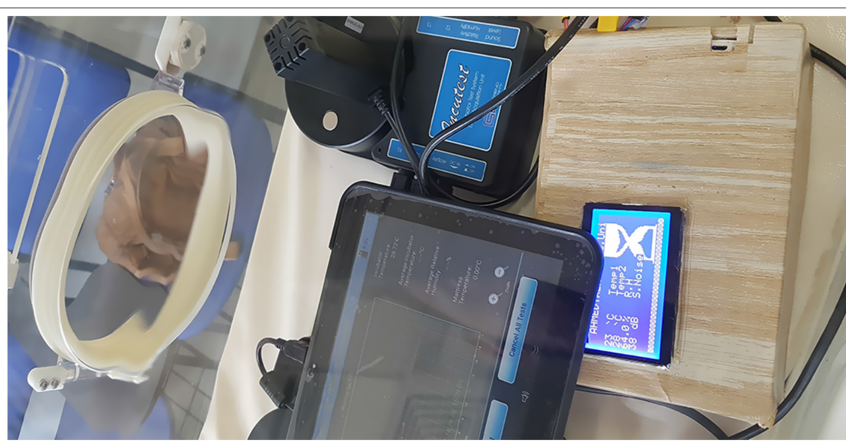

Fig. 7. Testing our device in a Drager Isolette Infant Incubator with a Datrend IncuTest incubator Tester.

TABLE II. RESULTS OBTAINED FROM TESTING OUR DEVICE IN A DRAGER ISOLETTE® INFANT INCUBATOR WITH A DATREND INCUTEST INCUBATOR TESTER

	Drager Isolette® Infant Incubator	Datrend InuTest	Our Incubator Analyzer		
			Air Temp	Mattress Temp	Relative Humidity
Temperature	29.0°C	28.73°C	28°C	26°C	64.0%
	30.5°C	29.81°C	29°C	27°C	58.0%
	31.5°C	31.29°C	30°C	27°C	54.0%
	33.0°C	32.32°C	31°C	28°C	50.0%
	34.4°C	33.29°C	34°C	30°C	44.0%
	35.2°C	34.65°C	35°C	31°C	39.0%
Sound Noise		41.2 dB		39.0 dB	

TABLE III. RESULTS OBTAINED FROM TESTING OUR DEVICE IN A DRAGER ISOLETTE® INFANT INCUBATOR WITH A DATREND INCUTEST INCUBATOR TESTER

	Girffe OmniBed Incubator		Fluke INCU Incubator Analyzer		Our Incubator Analyzer	
	Mattress	Air	Mattress	Air	Mattress	Air
Temperature	36.5°C	36.6°C	35.3°C	37.2°C	35°C	36°C
	36.9°C	36.8°C	36.4°C	37.8°C	36°C	36°C
	36.9°C	36.8°C	36.4°C	37.8°C	36°C	36°C
Relative Humidity			31.00%		31%	
			31.20%		31%	
			31.30%		32%	
Sound Noise			61.6 dB		40 Db	

C. Sound Noise Sensor

The designed sensor was implemented on Proteus. We were unable to get an actual simulation because of the simulator's inability to provide any audio input. The designed circuit was tested and calibrated using an android application and the obtained readings were quite accurate. We first tested the sensor in a quiet room and the obtained reading was 37 dB as compared to 39 dB on the android application. Then, we tested the sensor with some music turned on to check the sensor accuracy, and the reading obtained was 69 dB as compared to 73 dB on the android application.

D. Testing the Final Implementation

We installed all sensors together in one circuit and performed appropriate adjustments to the source code in order for all these components to function simultaneously in harmony. We implemented a simulation on Proteus to test the circuitry and the code. We also implemented the circuit on a testing board and burned our source code into the Atmega32. The circuit and code were found to be working properly. After final implementation and testing, the device was enclosed and put together in a box. The designed approach was tested and compared to other infant incubator analyzers. We tested our device in a Drager Isolette Infant Incubator (Model C2000), and at the same time, in a Datrend IncuTest incubator Tester (Fig. 7). Data in Table II show the obtained results. The Drager Isolette does not provide a mattress heating mechanism.

In the second test, we tested our device in a Giraffe OmniBed Incubator with an Intensive Neonatal Care Unit (INCU) Fluke infant incubator analyzer (Fig. 8). Data in Table III show the obtained results.

IV. DISCUSSION

These analyzers are supposed to check the value of the current parameters which corresponds to safety standards. In this study, we investigated the major parameters that affect neonates' health directly and their safety standards. We also studied the possible ways to monitor and measure these parameters which are produced by the infant incubator. This study has focused on using unsophisticated electronic sensors and components for the design. We used LM35 and DHT11 sensors to obtain temperature values. Both sensors provided accurate measurements. LM35 was shown to have a

Fig. 8. Testing our device in Girffe OmniBed Infant Incubator with a INCU Fluke incubator analyzer.

greater response time and accuracy in conduction measurements. DHT11 temperature readings had a fast response time, as well as better sensing response to convection and radiant temperature. These particularities get along with our aspirations to use LM35 to obtain temperature from the incubator mattress and to use DHT11 as a measuring tool for the air temperature inside the infant incubator chamber. Humidity measurement was also made by the DHT11 sensor. Despite that this sensor is no use below 20% or above 90%, recommendations say that the perfect humidity for neonates is a level between 30% and 50%. This makes the DHT11 appropriate for our use. Humidity readings we obtained from DHT11 were accurate as desired.

With no specific sound noise sensors in the market are available for such uses, we designed our own sensor using a condenser microphone and an LM386 amplifier. Due to the non-linearity between the ADC value and the dB, we were unable to obtain a common constant multiplier for all ADC values. The obtained readings from our designed sensor were compared to android SPL application readings. We have obtained nearly accurate measurements with an error rate up to $\pm$10 dB. The readings obtained from our sensor were convergent to those readings from the android application. Further advanced optimization to this sensor is recommended. The resulting test, presented in Table II and Table III, has evidenced a minor lack of accuracy and response regarding temperature measurements compared to the other analyzers, especially in high temperatures. Initially, we attribute that to the amount of sensors in other analyzers where multiple (around four) temperature sensors measure the temperature simultaneously. Also, the design of these sensors in the other analyzers is designed to operate for such specific applications. However, this deficiency could be improved by some software optimization. Relative humidity measurements were accurate compared to the Fluke INCU analyzer. The Datrend Incutest analyzer had a problem with its humidity sensor; therefore, we were not able to compare the relative humidity results. Sound noise measurements had a problem and a major lack of accuracy, especially with high measurements. During the test, our sensor demonstrated some impracticality that could be resulted from the hardware design. The error ratio exceeded $\pm$20 dB. However, this also could be improved by further software optimization.

In conclusion, this study details a fundamental design approach for an infant incubator analyzer that can be manufactured at low cost by Turkish local manufacturers. The proposed design is a preliminary prototype that needs further optimization and testing. A major limitation in this study should be recognized. We were unable to design a highly advanced sound noise sensor due to the limitation of time and resources. More efforts are needed to develop a highly advanced and accurate sound sensor suitable for this particular application which involves neonate's safety. Design recommendations generated from this study are intended to influence future designs. Major aspects to be considered encompass airflow as well as other measurements that are not available in existing infant incubator analyzers which are very important for the neonate's safety and those are oxygen saturation and light intensity measurements. Moreover, future designs should consider accordance to the IEC 601-2-19, IEC 601-2-20, and IEC601-2-21 standards.

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