Design of Low Cost Temperature Controlled Neonatal Transportation Device

By

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A master thesis

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Declaration

I, the undersigned, declare that this thesis is my original work. It has never been presented for a degree in any other institution and that all sources of materials used in it have been duly acknowledged.

Name: ___________________________

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This MSc. thesis has been submitted for examination with my approval as an advisor.

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Certificate of Examination

This is to certify that the thesis prepared by Liya Befekadu entitled ***'Design of Low Cost Temperature Controlled Neonatal Transportation Device'*** submitted in partial fulfillment of the requirements for the degree of Master of Science in Biomedical Engineering (Bioinstrumentation and Imaging) complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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Abstract

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Temperature instability in preterm neonates is one of the major causes of morbidity and mortality. The immature systems and organs of preterm neonates in combination with poor facilities and after birth care lead to lifelong health complications, if not death. The drop of temperature in preterm neonatesneonate highly increases while they are transported through the embrace of nurses from delivery rooms to Neonatal Intensive Care Units (NICUs) in referral hospitals. They may also be transported by ambulances for large kilometers, because NICUs in Ethiopia are found only in referral hospitals. A significant drop of temperature in the surrounding environment during transportation makes the preterm neonates hypothermic and affects the whole function of their body. Therefore it's necessary to measure and optimize the neonates' body temperature to the normal level while they are being transported.

In order to solve this problem, in this thesis we have designed and prototyped a novel portable device that can be used to transport the neonates in a temperature controlled environment. We believe that this device, once fully developed and implemented, can save thousands of lives of preterm neonates and avoid the pain caused to parents due to lose of their new born babies. The price and simplicity of our design makes it convenient for use in low resource settings and low income countries like Ethiopia.

In our design, we have used temperature sensors and microcontroller to measure the body temperature of the preterm neonates and make the right decisions. Heater and fan are used to generate and circulate heat around the preterm neonate. Based on the temperature reading obtained from the temperature sensors, the microcontroller decides whether or not to turn the heater and fan ON. The system uses display and alarm system to give signal for the physician about the neonate's body temperature.

Key words: preterm neonates, NICU, body temperature

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List of Abbreviations

Acronyms

AC	Alternating Current
ACP	Aluminum Composite Panel
BAT	Brown Adipose Tissue
DC	Direct current
LCD	Liquid Crystal Display
LED	Light Emitting Diode
NICU	Neonatal Intensive Care Unit
PCM	Phase Change Material
PTB	Preterm Birth
TPWM	Temperature Pulse Width Modulation
WHO	World Health Organization

Chapter 1 Introduction

1.1 Background

A newborn or neonate is a child under 28 days of age who needs appropriate treatment and is at highest risk of dying [1]. Neonatal deaths are defined as those occurring between 0-28 days in live-born neonates [2]. Globally, 4 million neonates die and of the 4 million neonatal deaths annually, 2.8 million occur in the first week of life (the early neonatal period) and 1.2 million between 8 and 28 days of life (the late neonatal period) [3]. This study represents almost 40 percent of all deaths in childhood which increase over time and relating with this increasing number, 98 percent of neonatal deaths occur in developing countries [3-4]. Therefore, it is necessary to provide appropriate feeding and care for the neonates to improve the chance of survival and to lay down the foundation of healthy life.

According to Ethiopian Demographic and Health Survey in 2016, in Ethiopia, high rate of neonatal mortality (29 deaths per 1,000 live births) is reported and preterm birth is believed to be a major and direct cause of neonatal mortality [5]. Preterm birth (PTB) refers to the birth of a baby that occurs before 37 completed weeks of gestation [6]. Babies born at PTB are considered as premature and sometimes referred as preemies. These premature babies can lose body heat rapidly, they don't have the stored body fat of a full-term neonate and they can't generate enough heat to counteract what's lost through the surface of their bodies [7]. Therefore, such premature neonates' deaths occur because their body become hypothermic ($<36.5^oC$) and can't resist changes in the environmental temperature. Hypothermia in preterm neonates can lead to breathing problems and low blood sugar levels [7].

In addition to their rapid drop of body temperature due to the incomplete weeks of gestation, their probability to become hypothermic increases while they are transported from delivery rooms to Neonatal Intensive Care Units (NICUs) for further treatment. Whether the transportation is through the embrace of the physicians in referral hospitals or through traditional ambulances from clinics to the referral hospitals which are the only places that NICUs can be available, the risk of exposing the preterm neonates to low temperature is high, thereby endanger their survival. In a country like Ethiopia, the survival of preterm neonates can be increased by implementing available and cost effective temperature controlled neonatal transportation device.

1.2 Statement of Problem

Preterm neonates have insufficient subcutaneous fat necessary for insulation, reduced amounts of brown adipose tissue (BAT), a limited ability to mobilize norepinephrine and fat for energy production, and a diminished capacity to increase their oxygen consumption [8-9]. Therefore, those preterm neonates lack the effective mechanisms of heat production and need immediate intervention to resist the temperature of external environment.

In Ethiopia, when preterm neonates get birth in clinics, they must be transferred to referral hospitals to get an appropriate treatment in NICUs. During transportation of those neonates to referral hospitals, the preterm neonates get hypothermia and most of them die or become in serious health complications. Even preterm neonates who get birth in referral hospitals which have NICUs, they face the same problem while they are transported from delivery rooms to NICUs through the wards of the hospitals because their body cannot resist the low environmental temperature. This eventually leads to high rate of morbidity and mortality of preterm neonates.

1.3 Objectives

1.3.1 General objective

The general objective of this thesis is to design low cost temperature controlled neonatal transportation device for neonates who are born prematurely before 37 completed weeks of gestation by keeping their body temperature at normal state during transportation.

1.3.2 Specific objectives

The specific objectives of this thesis are

- To identify the preterm neonate's body temperature while the neonate is transported to NICU from delivery rooms and from different clinics which give delivery services but do not have NICUs.
- To give efficient warming condition for preterm neonates while they are transported.
- To optimize the temperature of the neonate to optimal level when it increases or decreases from its normal level.
- To give information to the physician about the neonate's body temperature whether it's in a normal condition or not for the appropriate treatment.

1.4 Methodology

The design concentrates on preterm neonates' body temperature regulation. It uses temperature sensors which can be attached on neonates' skin and based on the detection; the system controls their body temperature using microcontroller, heater and fan. Before prototyping, the design is tested by using proteus software version 7.10 to ensure each part will function properly. After the test on proteus software, the prototype is manufactured to show how the system works with temperature variations. On the prototyping, C program is used to code Arduino Atmega328P microcontroller to regulate the output of heater and fan based on the temperature sensor reading. The compartment of electrical circuit is made by Aluminum composite panel (ACP) material and the neonate's bed chamber is made by transparent acrylic sheet with comfortable sponge covered by synthetic leather.

1.5 Literature Review

The first challenge that a newborn neonate faces after birth is maintaining a normal body temperature. Before birth, while the neonate is inside uterus, the fetus is under normal temperature surrounded by amniotic fluid at maternal body temperature. After birth, the new born will be exposed to a much lower environmental temperature. Following birth, there is a significant drop (more than $10^{o}C$) in the surrounding temperature [10]. So, the neonate will be hypothermic which is so dangerous. This becomes even worse when the neonate is preterm due to the immaturity of multiple organ systems and places it at high risk for a variety of complications.

1.5.1 Heat transfer in neonates

Similar to any physical objects, there are four mechanisms through which heat can be transferred from neonates to the environment [11]. These are radiation, conduction, convection and evaporation. All these heat transferring mechanisms contribute to unstable thermal environment for the neonate.

Radiation is heat transfer via the emission or absorption of electromagnetic radiation [12]. Any object with a temperature greater than absolute zero (0 Kelvin) emits radiant heat [12]. Heat transfer through radiation is related to the temperature of the surfaces surrounding the neonate but not in direct contact with the neonate [13]. The newborn neonate emits heat energy in the form of infrared electromagnetic waves [13].

Another means of heat transferring mechanism is conduction which is the transfer of heat through direct contact between a neonate and an object with different temperature [11]. The third way of heat transferring mechanism in neonates, called convection, is the transfer of thermal energy from the molecules of the body to the molecules of an adjacent gas [11]. Heat is lost through convection when air currents pass over an neonate body, carrying its heat away with them [14].

The last one which is called evaporation is defined as the total heat transfer by energy-carrying water molecules from the skin and respiratory tract to a drier environment [11]. It is the loss of heat when water is lost from the skin of the neonate. In the extremely low birth weight neonates, evaporative heat loss is the major form of heat loss during the first week of life and exceeds total heat production [15]. The four heat transferring mechanisms are shown below on figure 1-1.

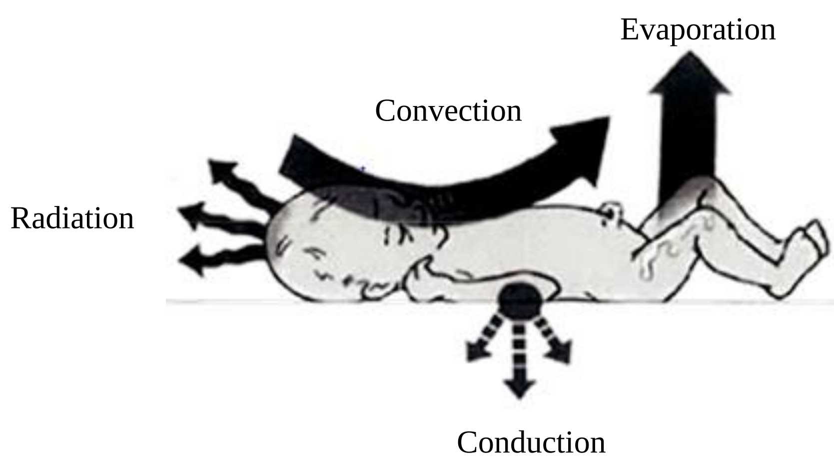


Figure 1-1: Mechanism of heat transfer in neonates

1.5.2 Previous works and current devices

Even though there are many technologies that can be used to warm preterm new born neonates, they can't function properly without reliable infrastructure and power supply. Prevention of hypothermia is therefore an essential aspect of neonatal care especially in the immediate neonatal period in low resource settings [16-18]. In this case different interventions for preventing and management of hypothermia have been performed. One of these which was performed in community as well as in hospital settings is the ‘warm chain’ which is a set of 10 interlinked procedures which must be undertaken at birth and during the following few hours and days to prevent hypothermia by minimizing heat loss in all newborns. The 10 steps of the ‘warm chain’ procedure are as follows:

(a) Warm delivery room;

(b) Immediate drying;

(c) Skin-to-skin contact;

(d) Breastfeeding;

(e) Bathing and weighing postponed;

(f) Appropriate clothing/bedding;

(g) Mother and baby together;

(h) Warm transportation;

(i) Warm resuscitation and

(j) Training and awareness rising.

Resuscitation is an emergency care which helps a neonate who is not breathing or having difficulties with breathing at birth [19]. The limitation of warm chain method is failure to implement any one of these procedures which will break the chain and put the newborn baby at risk of hypothermia [20].

Several studies have demonstrated the success of utilizing polyethylene occlusive wraps to keep preterm neonates warm at the time of delivery [21-23]. Polyethylene occlusive wrap is a type of plastic which is good moisture barrier with poor oxygen blockade [24]. Following delivery, healthcare providers place the wet neonate into a polyethylene bag, keeping the neonate’s head exposed. The head and face are then dried, and resuscitation continues. The clear plastic wrap permits visualization of the neonate and any needed interventions are performed while the neonate is in the bag. For more extensive resuscitation requiring umbilical or peripheral lines, healthcare providers cut holes in the bag to gain an access. The neonate is then placed on warmed blankets and transferred to NICU. Polyethylene bags permit heat to be gained by the neonate through radiation when the skin temperature is less than the temperature of the surrounding objects and reduce the amount of evaporative heat loss. The use of polyethylene bags has been demonstrated to work in neonates less than 28 weeks' of gestation [8]. Figure 1-2 shows how polyethylene bag is used to warm an neonate.

Figure 1-2: Polyethylene bag to warm a neonate

The limitation of using polyethylene bag is during prolonged resuscitation; the wrap will more likely move away or dislodge for a number of seconds while resuscitation is performed [9], which leads to loss of heat from the neonate. In addition to this polyethylene bag has limitation due to its potential to cause hyperthermia in newborns and it doesn't have temperature controlling mechanism [25].

Another currently available device which is used to warm up the premature newborn neonate is neonatal smart jacket which is shown on figure 1-3 below. It is a wearable unobtrusive continuous monitoring system realized by sensor networks and wireless communication, suitable for monitoring neonates outside the incubator [26].

Figure 1-3: Neonatal smart jacket

In the area of body sensor networks, as the number of body signals and sensors increases, it is no longer feasible for each sensor or sensor modality to take another set of wires, amplifier box, power supply, etc. In this case, it becomes essential to embed multiple sensors in a single carrier (such as a baby jacket), sharing power sources and sharing wireless channels. Therefore it needs high technology and not feasible for low resource settings [26].

The very recent design which is done to warm premature neonates is embrace neonate warmer. The design looked something like a sleeping bag wrapped around a premature neonate and a pouch of phase change material (PCM) kept the baby's body at exactly the right temperature and maintained this temperature up to four hours [27]. After four hours, the PCM pouch could be recharged by submerging it in boiling water for a few minutes [27]. Figure 1-4 shows the embrace neonate warmer. The limitation of this design is the absence of any form of temperature controlling mechanism in the whole system [28]. This puts the preterm neonate endanger during times when hyperthermia occurs.

Figure 1-4: Embrace neonate warmer

This thesis project is intended to design neonate transportation device which is feasible for low resource settings with good and effective temperature controlling mechanism. It is designed to keep the neonate's temperature at normal level by placing the neonate inside the device with simple and a few steps. The design is done with an intension of providing simple neonate warmer with affordable price in low resource setting areas. It includes alarm system and temperature display to inform the physicians about the preterm neonate during transportation to NICUs for further treatment.

1.6 Significance of the thesis

The increased number of premature neonates' birth and their immature system of temperature regulation with lack of NICUs in every clinic bring large number of deaths. Temperature instability in preterm neonates increases during transportation of neonates from place to place for further treatment because there is high environmental temperature variation. This project thesis is intended to design a portable warmer which can keep the temperature of neonates during transportation. It aims at saving the lives of premature neonates in low resource settings and also prevents health complications on neonates that are caused by problems related with temperature instability.

1.7 Scope and delimitations of the thesis

The design is intended to work on controlling the temperature of preterm neonates who are transported to NICUs for further treatment. It's more concerned in designing cost effective and efficient warmer to control the temperature of preterm neonates and to prevent hypothermia. As it is intended to be used in low resource settings, the reading of electroencephalography (EEG), electrocardiography (ECG) and pulse rate of the preterm neonate is not included in this design.

1.8 Organization of the manuscript

The thesis is organized in six chapters. Chapter 1 provides background information, problem statement and objectives of the thesis and also some literature reviews. Chapter 2 discusses body temperature management, the difference between neonates and adults body temperature regulation and the preferable sites to take the neonates' body temperature measurement.

Chapter 3 provides a description on materials and methods of effective neonate warmer design. It also explains all design alternatives and design matrix with final output. Chapter 4 presents results and discussions based on the proteus test and prototype manufacturing. Finally chapter 5 offers conclusion and recommendation on the whole design process.

Chapter 2 Body Temperature Management

2.1 Regulation of Body Temperature

Regulation of body temperature is controlling the balance between heat production and heat loss of body. It is dependent on an intact central nervous system, the ability to produce heat, the availability of oxygen, and an energy source [8].

Normally animals use two types of methods to maintain their body temperature. According to their methods they are called endothermic and ectothermic animals. Endothermic animals gain their body heat from metabolic reactions within their body whereas ectothermic animals rely mainly on the environment to gain essential body heat [29].

Humans and other mammals are endotherms and control their body temperature within a very narrow range. The control of human body temperature is coordinated by the part of the brain known as hypothalamus. Hypothalamus is located at the base of the brain as shown on figure 2-1. It regulates the body at normal temperature range based on the information from skin and internal body thermoreceptors. Temperature receptors detect changes in the external environment and send the information to hypothalamus of the brain which acts like a processing unit. According to the information from thermoreceptors, hypothalamus trigger changes to sweat glands and muscles to ensure normal temperature level for the whole body [29].

Figure 2-1: Hypothalamus

Figure 2-2 explains how hypothalamus controls the whole body temperature with respect to its negative feedback set in mechanisms to return the body temperature to its normal or set level.

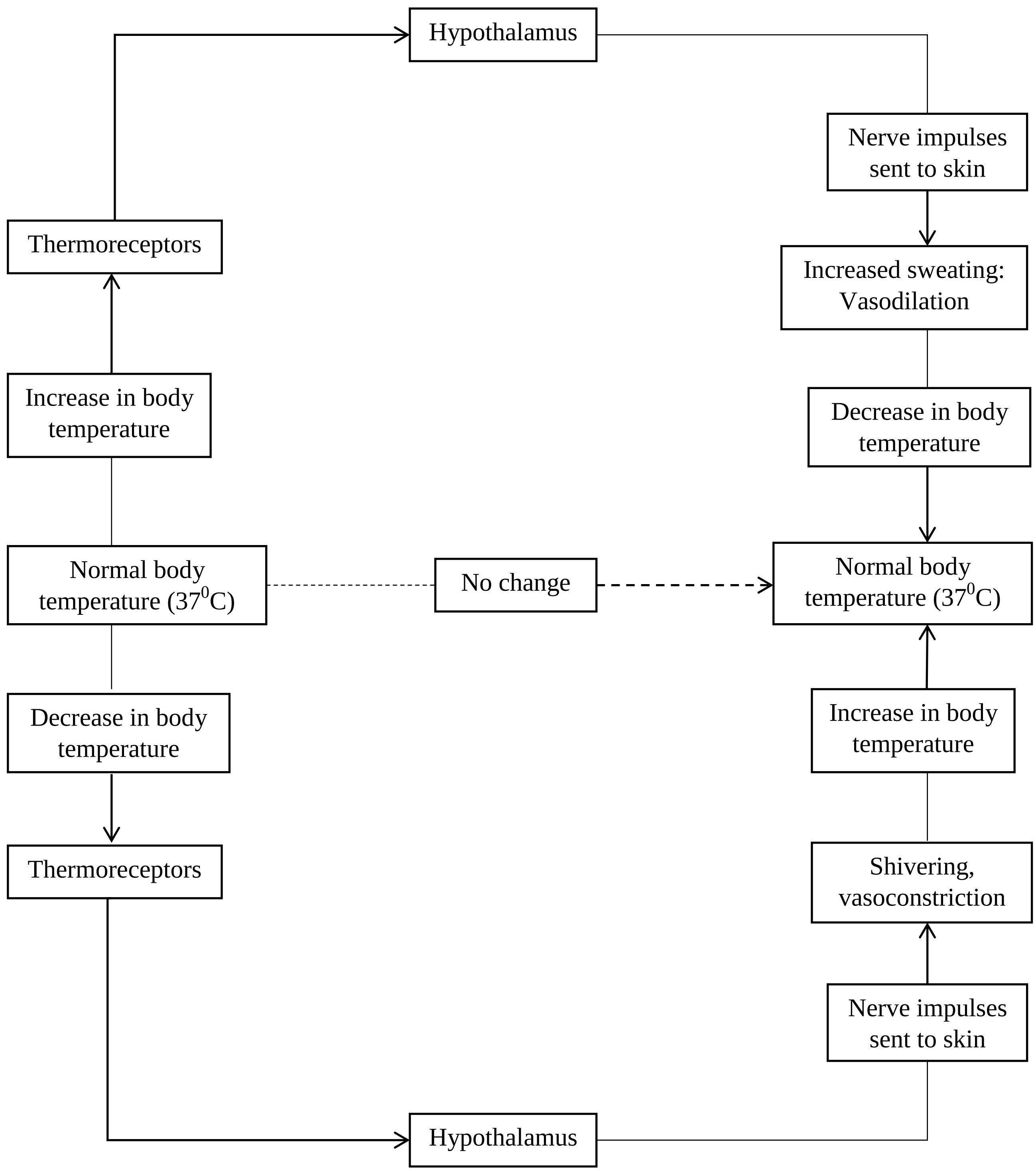


Figure 2-2: Negative feedback system of hypothalamus temperature management

2.2 Preterm neonates' body temperature management

Thermal regulation in preterm neonates is different from adults. In adults, the response to cold body temperature includes peripheral vascular constriction, inhibition of sweating, voluntary muscle movements, involuntary muscle movements (shivering) and non-shivering thermogenesis [21]. In case of preterm neonates the main mechanism that is used for heat production is non-shivering thermogenesis (metabolism of brown fat) [8] [21].

Non-shivering thermogenesis is the primary method of heat production in neonates. It is production of heat by the metabolism of brown fat. The metabolism of brown fat increases body temperature when the thermal receptors in the skin detect a decrease in skin temperature. Brown fat is a special kind of highly vascular fat found in neonates. As shown on figure 2-3, brown fat is localized around the adrenal glands, kidneys, back of the neck, in the axillae, sternum, between the scapulae and along the abdominal [30].

Figure 2-3: Location of brown fats in neonates

Non-shivering thermogenesis begins when the thermal receptors in the skin detect a decrease in skin temperature and transmit the signal to the hypothalamus thermal center. In response to the hypothalamic stimulation, norepinephrine is released in brown fat to initiate its metabolism. As brown fat is metabolized, it generates more heat than other fats. Thus, blood passing through the brown fats is warmed and carries heat to the systemic circulation or to the rest of the body [30-31].

2.3 Range of neonates' body temperature

A normal state of temperature in which the body can function properly is called normothermia [8]. When neonate's body loses heat faster than its heat production, its temperature will be lowered and called hypothermia and it's caused by exposure of body to cold environment [7]. If hypothermia occurs and left untreated, heart, nervous system and other organs can't function properly and it causes failure of heart and respiratory system and also death [7]. On the other hand, when a body produces or absorbs more heat than it dissipates and fails its thermoregulation, hyperthermia will occur [7]. Hyperthermia also needs immediate treatment otherwise disability or death may occur [8]. The range of neonate's body temperature is listed on Table 1.

Table 1: Range of neonates' body temperature [8-9]

Thermal Environment	**Temperature Range (^{o}C)**
Hyperthermia	>37.5
Normothermia	36.5-37.5
Mild hypothermia	36-36.5
Moderate hypothermia	32-36
Severe hypothermia	<32

2.4 Sites for monitoring temperature in neonates

Body temperature measurement can be taken orally, rectally, abdominally, axially and from the shoulder blades as shown on figure 2-4 [9].

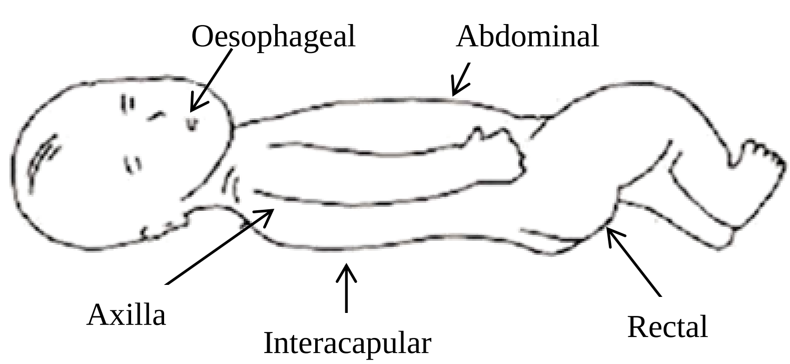


Figure 2-4: Site of body temperature measurement

The most commonly used site for monitoring temperature in neonates is the skin. Continuous monitoring of the abdominal skin temperature is non-invasive method that has shown good correlation with rectal temperature which is believed to be close approximate with the neonates' core temperature [9].

2.5 Neonatal Intensive Care Unit (NICU)

NICU is an intensive care unit created for preterm and sick neonates who need special treatment. It contains equipment which are designed for neonates and medical staffs who are trained in giving these services for those neonates. A lot of special equipment are used to monitor and support the neonates' vital functions such as pulse, breathing, blood pressure and temperature. Most neonates admitted to NICU are premature, have some problems during delivery or show some signs of medical issues that require special care.

Chapter 3 Materials, Methods and Design

3.1 Design alternatives

Criteria are the specifications a design solution must meet or the attributes it must possess to be considered successful [32]. It helps to provide direction toward the solution. Safety of the neonate, effectiveness of the equipment, preterm neonate's comfort, the maximum limit of time that the warmer functions, ease of use for the physicians and cost are list of preliminary criteria in this design for a better solution.

The next step in the design process begins with creativity in generating new ideas that may solve the problem [32]. According to this, four design alternatives are proposed to fulfill the identified problem on preterm neonates.

3.1.1 Design 1 - Using warm water circulation

The first design idea is to design the warmer by using boiled water. Figure 3-1 shows the sketch of this design. In this design the body temperature sensors, microcontroller, heater and water will be used to maintain the temperature of the neonate. At first the temperature sensors will be attached on the neonate's body and its reading will be the input for the microcontroller and the output pin of the microcontroller will be connected to the heater. Heater is The microcontroller will be programmed to start up the heater if the neonate is hypothermic and to close it if the temperature of the neonate is in the normal range or hyper thermic according to the temperature sensors' output. The heater will be inserted in the water bag to boil the water which will circulate under the fabric cover wrapper. The zigzag line on figure 3-1 shows the circulation tube of the water. The boiled water is used to generate heat for the neonate. The box found below the wrapper is used to put the water bag, heater, microcontroller and battery. This box will be unplugged at times the wrapper will be cleaned.

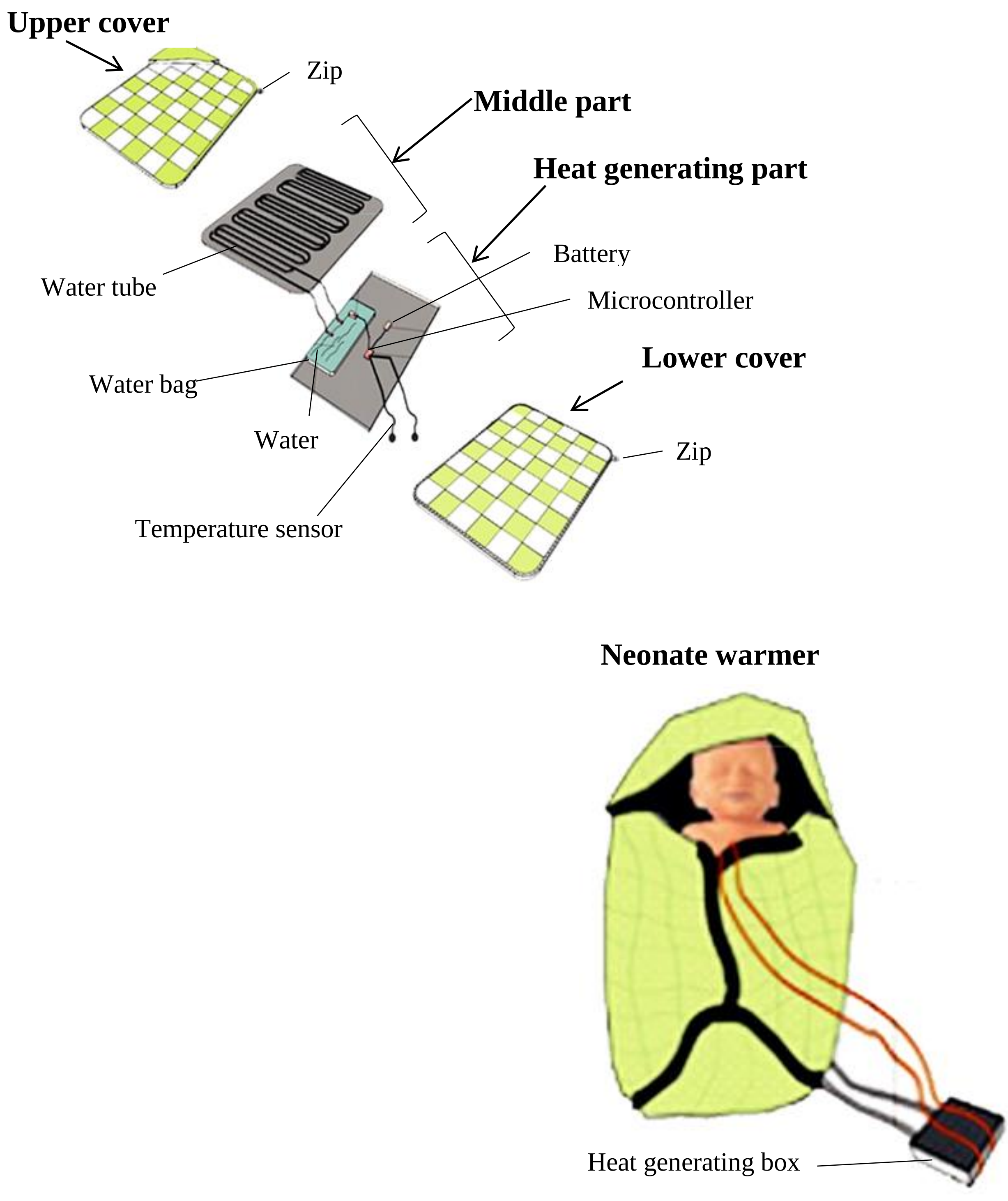


Figure 3-1: Design 1- Using boiled water circulation

3.1.2 Design 2 - Using fan and heater

The working principle of the second design idea uses body temperature sensors, microcontroller, heater and fan to warm the neonate. The sketch of this design idea is shown on figure 3-2.

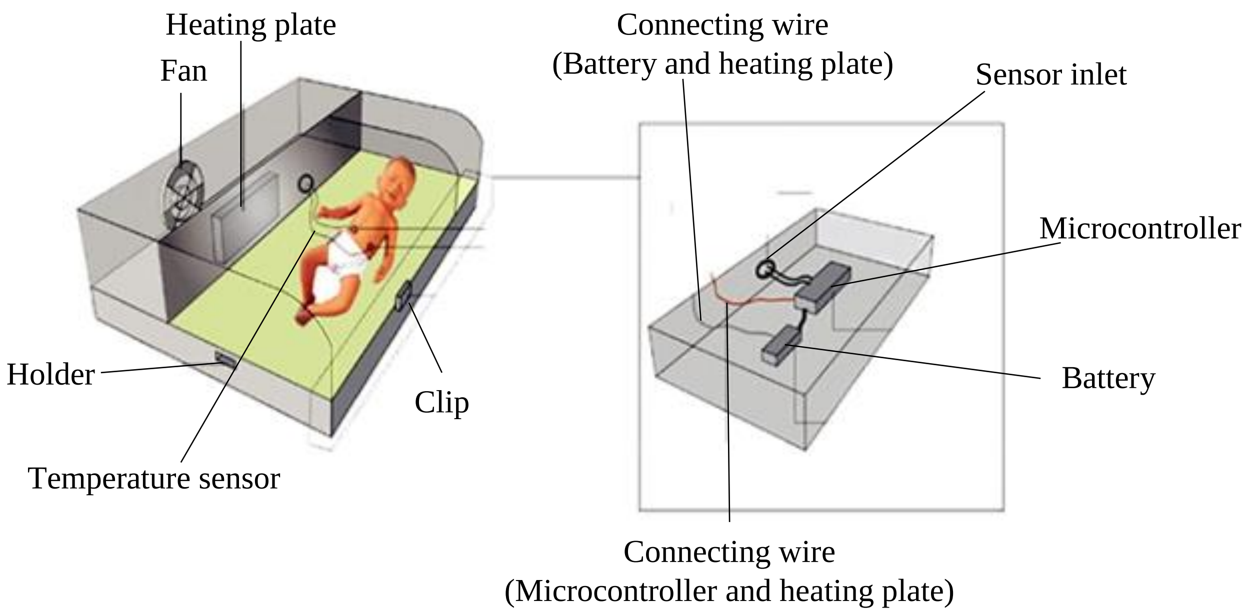


Figure 3-2: Design 2- Using fan and heater

The temperature sensors will be attached on the neonate's body and its reading will be the input for the microcontroller and the output pin of the microcontroller will be connected to the heater. The microcontroller will be programmed to start up the heater if the neonate is hypothermic and to close it if the temperature of the neonate is in the normal range or above normal according to the sensors' output. The hot air from the heater will circulate around the neonate by using fan. The "L" shape box which is found around the bottom and left side of the bed is used to put fan, microcontroller and heater. The material will be box like structure and only the mattress which the neonate lays down on it will be washed during cleaning. The upper part of the neonate will be covered by transparent material.

3.1.3 Design 3 - Using resistive heating element

The third design idea uses resistive heating element under the fabric cover of the neonate wrapper and its sketch is shown on figure 3-3.

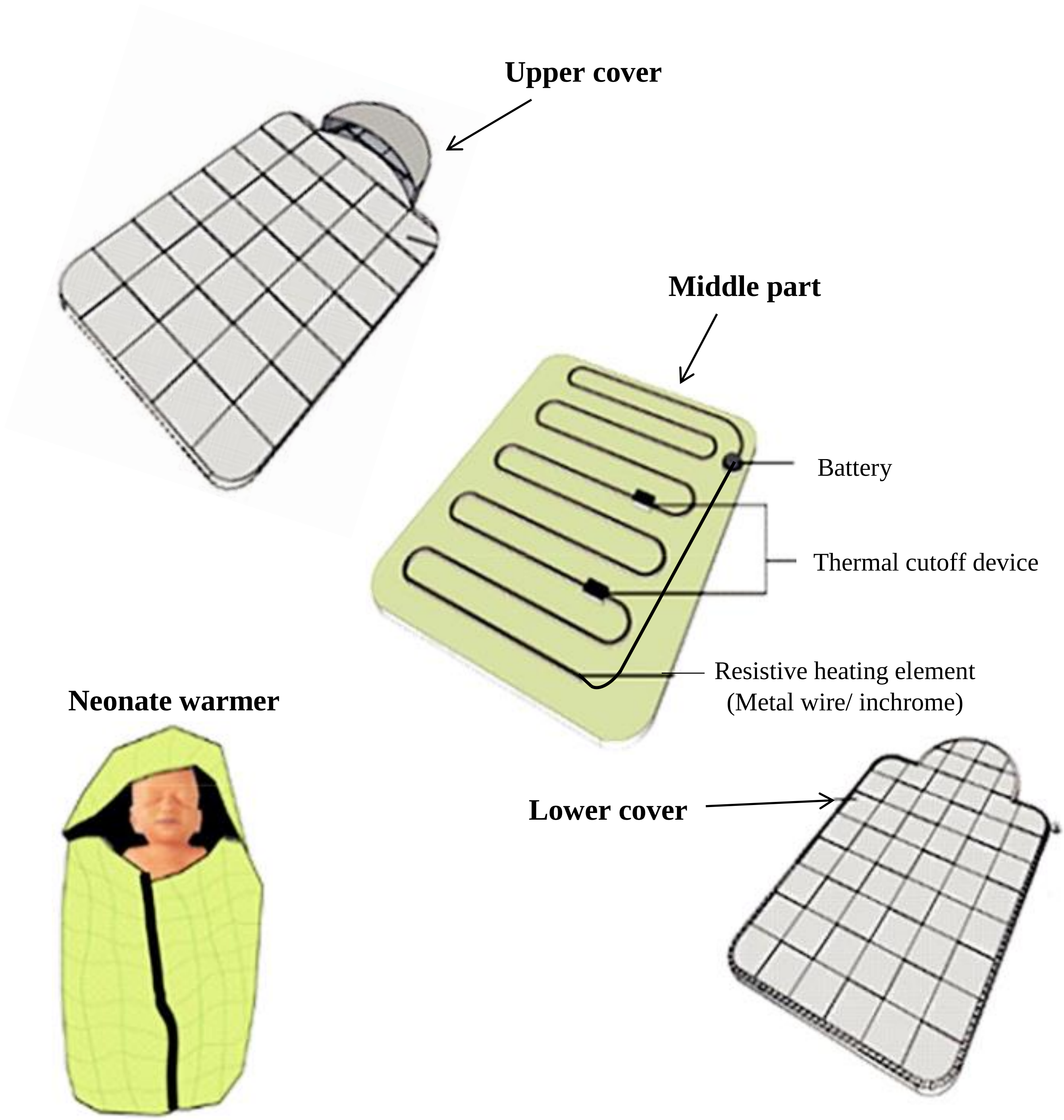


Figure 3-3: Design 3- Using resistive heating element

The idea of this design is to use the flow of electric current from the battery through the resistive heating element to generate heat for the neonate. The thermal cutoff devices set in the middle of the resistive heating element will be used to interrupt the electric flow at a specific temperature.

The zigzag line of figure 3-3 is the resistive heating element inside the wrapper within the fabric cover. This design does not use temperature sensors because any increase in temperature by the flow of electric current will be controlled by cutoff devices and the overheating will be avoided. The upper and lower cover of the wrapper will zip up together by putting the fabric cover in the middle. The heat from this heating element is used to warm up the neonate.

3.1.4 Design 4 - Using infrared heat

The fourth design idea uses infrared heat. The sketch is shown on figure 3-4. By adjusting the voltage applied to the incandescent lamp, the visible light will be reduced and the infrared heat will be produced [33]. This infrared heat will be controlled by microcontroller according to the temperature sensors' reading from the neonate's body. The microcontroller will disconnect the applied voltage to the incandescent lamp when hyperthermia occurs on the neonate and connect it when the neonate become hypothermic based on the neonate's body temperature reading from body temperature sensors. The neonate will lie inside the open box like structure and warmed by the infrared heat from the lamp. The curve structure above the bed is for the physician to hold the neonate.

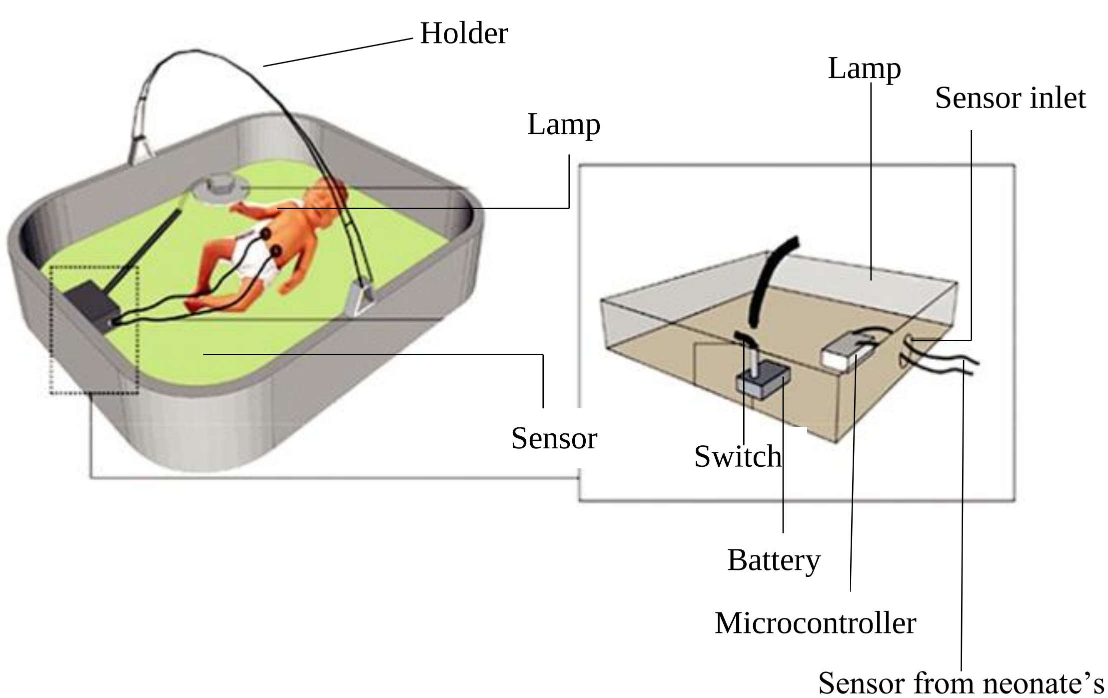


Figure 3-4: Design 4- Using infrared heating

3.2 Design matrix

Before deciding which design solution to implement, each alternative solution needs to be analyzed against the defined selection criteria [32]. One widely used method to formalize the decision making process is the design matrix. The design matrix is a mathematical tool that can be used to derive a number that specifies and justifies the best decision [32]. The first step in design matrix is to rank the desirable attributes or criteria in order of importance for the design solution.

Based on this rank the highest weight which is 30 is given for safety because the safety of the neonate is the highest priority in the design of this neonate warmer. The device should be safe for neonates' use and should consider the material's insulation and resistance against an increase in temperature due to heat generating material. It also checks the choice and durability of the design during sanitization. The safety criterion looks attentively to the material non-immunogenic nature during contact with the neonate's skin.

The second highest weight, which is 25, is given for the effectiveness of the warmer to evaluate the its perfect performance. This criterion considers the effective functionality of the whole system to give the better support for the preterm neonate under treatment. It also looks the accuracy of the warmer in adjusting the neonate's body temperature measurement.

The third highest weight is given for the comfort of the neonate to accomplish the objective of giving a better life for the preterm neonates on their first day of life. Its value factor is 20. These criteria deals about the type of the mattress which the neonate will have direct contact. It also checks whether the warming system will have effective heat circulation around the neonate's body with good access to the physicians.

Operating duration takes middle weight which is 15. It measures the time the warmer takes to start up the system and also the time length it waits in function without interruption.

Cost and ease of use are given the lowest weight, each one 5, because the main focus of this design is for the perfect temperature control and comfort of the neonates rather than the physicians. Ease of use measures the steps it takes to wrap the neonate during transportation and the time it requires to put the neonate under the system. It also considers the time the design requires for training the physicians on how to use. The total value of weights is 100.

Next each design alternatives are evaluated according to the stated criterion. A rating factor is assigned to each solution with the scale shown on table 2, which explains how well that solution satisfies the given criterion. The rating factor is on a scale of between 0 and 5 with 5 as best.

Table 2: The scale of rating factor

Scale	**Rating factor**
Excellent	5
Good	4
Fair	3
Poor	2
Unsatisfactory	1

Based on this rating factor scale the design matrix is done on table 3.

Table 3: Summary of design matrix

Design idea (weight)	Using boiled water circulation 		Using fan and heater 		Using resistive heating element 		Using infrared heat 	
Safety (30)	2	12	4	24	2	12	1	6
Effectiveness (25)	2	10	4	20	1	5	3	15
Patient comfort (20)	3	12	5	20	3	12	5	20
Operating duration (15)	2	6	4	12	3	9	4	12
Ease of use (5)	2	2	4	4	3	3	4	4
Cost (5)	3	3	2	2	4	4	5	5
TOTAL (100)	45		82		45		62	

As can be seen on table 3, after assigning a rating factor to each design alternative based on each of the specified criteria, the rating factor will be divided by 5, which is the maximum rating factor, and multiplied by the weight. Then it will sum down the column for each design alternative. The total sum at the bottom of each column determines the best design alternative [32].

3.2.1 Explanation on values of design matrix

The values assigned to each design alternatives based on each criterion is explained below:

Safety

Design idea 2 gets the highest score in safety because its electrical components have their own location in the box, unlike design idea 1 and 3 in which the heat generating components are placed inside thick fiber mattress. Because the electrical components of design idea 2 don't have direct contact with the mattress of the neonate, there is no immunogenic reaction on the neonate's skin.

Design idea 1 and 3 get the second highest score because the heat generating components of both designs are placed inside thick fiber mattress and unexpected tear up of the mattress may cause awful accident on neonate and can't give guarantee to it. Therefore, both designs fail in power surge protection. In addition to that there is temperature resistance failure in both designs because the wrapping mattress is flexible fabrics which cannot resist the increase in temperature up to $70^{o}C$.

Design idea 4 gets the lowest score because prolonged exposure of infrared heat can cause severe burn to skin and can permanently damage eyes [34].

Effectiveness

Design idea 2 gets the highest score in effectiveness because the fan helps to rotate the heat and the whole system doesn't take time to warm up and cool down. It uses temperature sensors and alarming system. As a result, it has perfect performance in temperature monitoring.

Design idea 4 gets the second highest score because even though the system works effectively, its performance decreases for the reason that the bag is open to the environment and the environmental temperature will affect the neonate's body temperature in parallel with infrared heat.

Design idea 1 gets the third highest score in the criteria of effectiveness because it takes few minutes (4 up to 5 minutes) till the circulating water boiled up and start controlling the neonate's temperature. It also takes time to cool down when the neonate's temperature is above normal. Due to this reason, design idea 1 compromises the perfect performance of the warmer on keeping the neonate's body temperature.

The lowest score in effectiveness is given to design idea 3 because it doesn't use temperature sensor and alarm system to show the neonate's condition. It works only at ON and OFF state without getting the reading of the neonate's temperature and can't manage the varying temperature of the neonate.

Patient comfort

Design idea 2 and 4 get the highest score on patient comfort criteria. Both design idea 2 and design idea 4 use flat mattresses which don't have direct contact with the heat generating components. In both designs the heat circulates equally around the neonate's body. And both designs also give good access to the physician.

Design idea 1 and 3 get the lowest score on patient comfort criteria because both designs use mattresses which make direct contact with the heat generating mechanisms. Also, the heat transfer in both designs is due to direct contact with the neonate's body. And also, both designs don't give good access for the physician.

Operating duration

Design idea 2 and design idea 4 both get the first highest score in criteria of operating duration because both designs don't take time to start working and also can function during long distance transportation without distraction.

Design idea 3 gets the second highest score because even though it can function for long distance transportation without interruption, it takes few minutes till the resistive heating element heat up. It also takes time to cool down when the thermal cutoff device disconnects the heat transmission.

Design idea 1 gets the lowest score because it takes time till the circulating water boiled and starts functioning and also takes time to cool down when the neonate temperature is normal and above normal. It also can't function for long durations because the boiling and cooling process of the circulating water will distract the continuous monitoring of the neonate warmer.

Ease of use

Design idea 2 and design idea 4 are easy to use because both have a bed which is prepared for the neonate with holdings for the physician. The steps taken to put the neonate under system are easy to understand because there is a place separated for the neonate to lie down. Therefore both get the highest score in these criteria.

Design idea 3 gets the second highest score because it uses wrapper around the neonate and needs more training hours on how to wrap the newborn.

Design idea 1 gets the lowest score because in addition to the training that needs on how to wrap, it has another load to the physician on transportation due to the bag which holds the water and electrical components at the bottom of the wrapper.

3.3 Final design

By compiling the results of the alternatives in the design matrix, design idea 2 which uses fan and heater with microcontroller and attached temperature sensors on the neonate's skin is the clear choice for the final design. Figure 3-5 shows the design with its diameters. This design received high rankings in all matrix categories. The lowest score it received was in cost which is because it uses fan with heater. What separates this design from the other three is its safety because the electrical components do not have any contact with the neonate and the preterm neonate will have its own separated bed and gets only the circulated heat. The 3D diagram of the final design with its diameters is shown on figure 3-5.

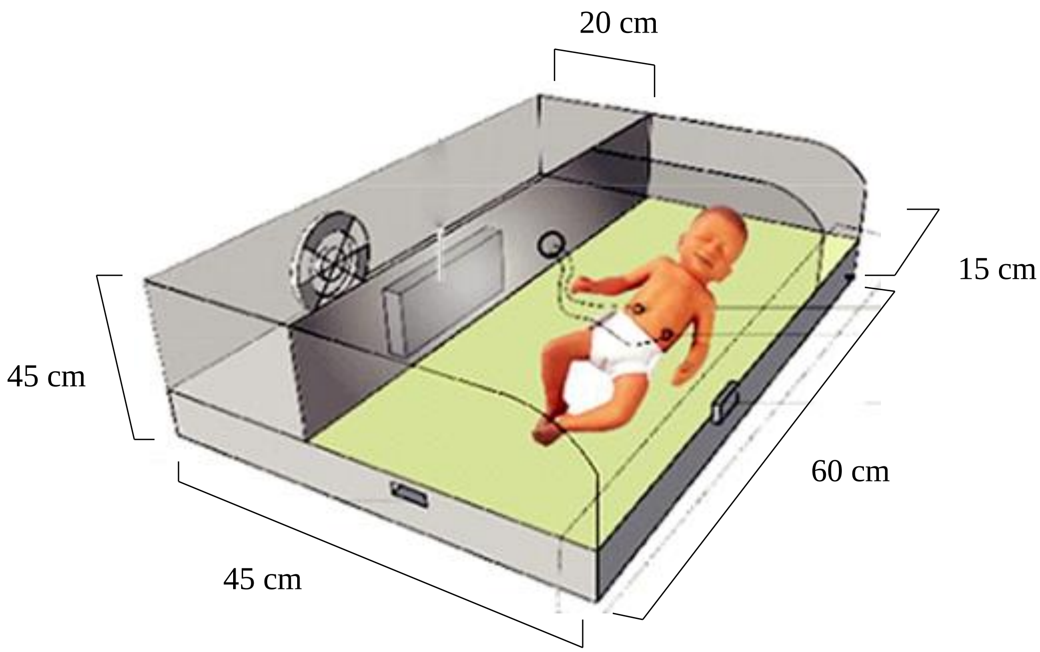


Figure 3-5: Final design

3.4 Cost

The materials and their prices for the prototype of this design are listed below on table 4.

Table 4: List of materials and their costs

Material	**Price (Birr)**
Microcontroller (Arduino)	7,500
Transformer	450
Fan	78.2
Board	250
Bread board (x3)	120
LCD	300
Relay	63
Buzzer	55
Electrical components	1,800
Prototype fabrication	14,000
TOTAL	**24,616.2**

Chapter 4 Results and Discussion

4.1 Test on Proteus Software

The design is tested through proteus software to ensure that each part will function properly during the practical modeling. The design is done using Arduino microcontroller Atmega 328P and C program is used to write the code. The entire code to function the system is written on Appendix.

4.2 Prototype

The prototype has three boards which are the main circuit control board, the fan control circuit board and the heater control circuit board. On the main control circuit board, Arduino Atmega328P microcontroller is used to control the whole system. Light Crystal Display (LCD) is adjusted to display the readings of the system which are set temperature(S), reading temperature (R), error (E) and temperature pulse width modulation (TP) which controls the circuit with a microcontroller's digital output. Buzzer and Light Emitting Diodes (LED) are used to show whether the system is giving the right output temperature or not. Figure 4.1 shows the main control circuit board design on proteus software and its connection on prototype.

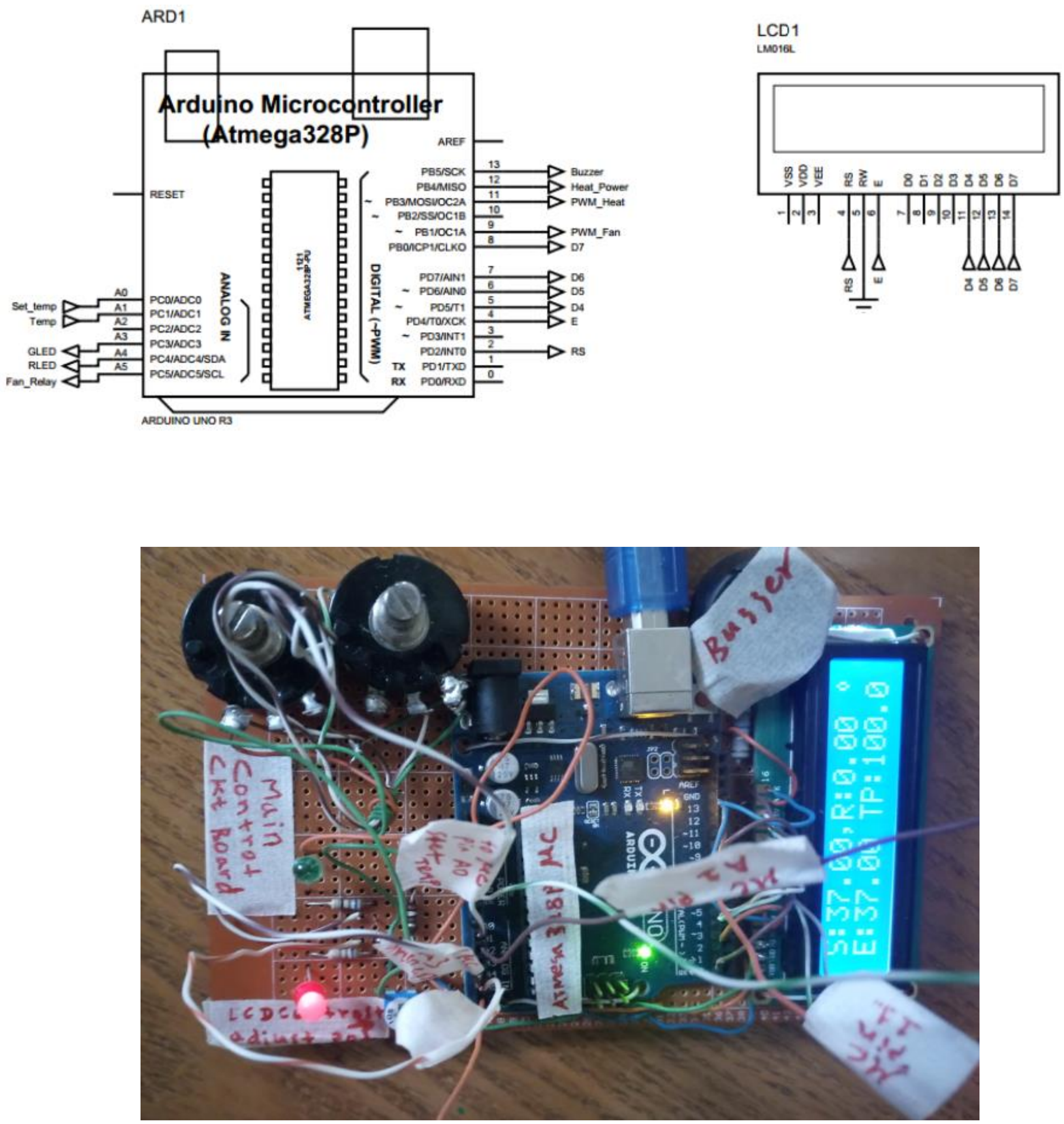


Figure 4-1: The main control circuit board

In the fan control circuit board, 220V AC power goes to transformer and 10V AC power from the transformer is rectified by rectifier diodes to DC power. The fan speed is controlled by potentiometer. Figure 4.2 shows the fan control circuit design on proteus software and its connection on the prototype.

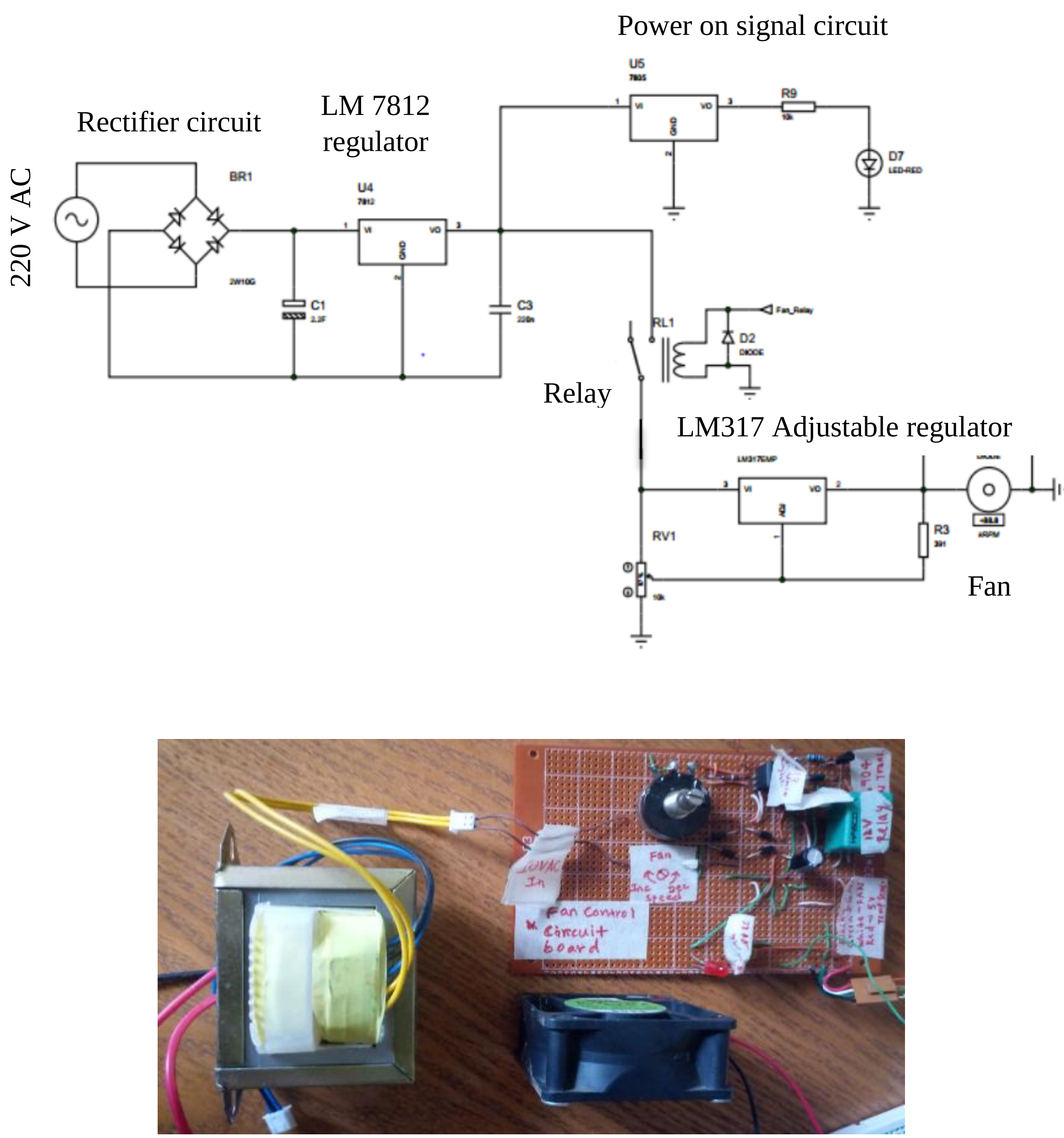


Figure 4-2: Fan control circuit board

To adjust the right output temperature reading, heater is used and controlled by the heater circuit. Figure 4-3 shows the heater control circuit board design on proteus software and its connection on the prototype. The inlet 220V AC power will be rectified by four 6A, 400V high voltage rectifier diodes and fuse is used for circuit protection. LED is used to signal that the system is functioning. MOSFET is used to adjust the heating values of the heater. Bread board is used as connecting point.

When the system starts working, the LCD display displays the texts which say “Welcome to neonate incubator….”, “Loading……” and “Please set the right temperature?” with 0.1 minute time interval. When the temperature is set at the right temperature using the set potentiometer, it displays “temperature set is successful!” After the set temperature is on the exact point, the heater and fan will be ON. When the temperature sensor reads below or above normal level, heater and fan give appropriate heat circulation under the regulation of temperature pulse width modulation. The design of the three circuit boards connected together on proteus software and on the prototype is shown on figure 4-4.

The result of the prototype during implementation is shown on Table 5.

Table 5: Result of the prototype

Set temperature	**Reading from temperature sensors**	**Heater**	**Fan PWM**
37^0C	34^0C	ON	Decreased
37^0C	35^0C	ON	Decreased
37^0C	37^0C	OFF	Increased
37^0C	39^0C	OFF	Decreased
37^0C	41^0C	OFF	Decreased

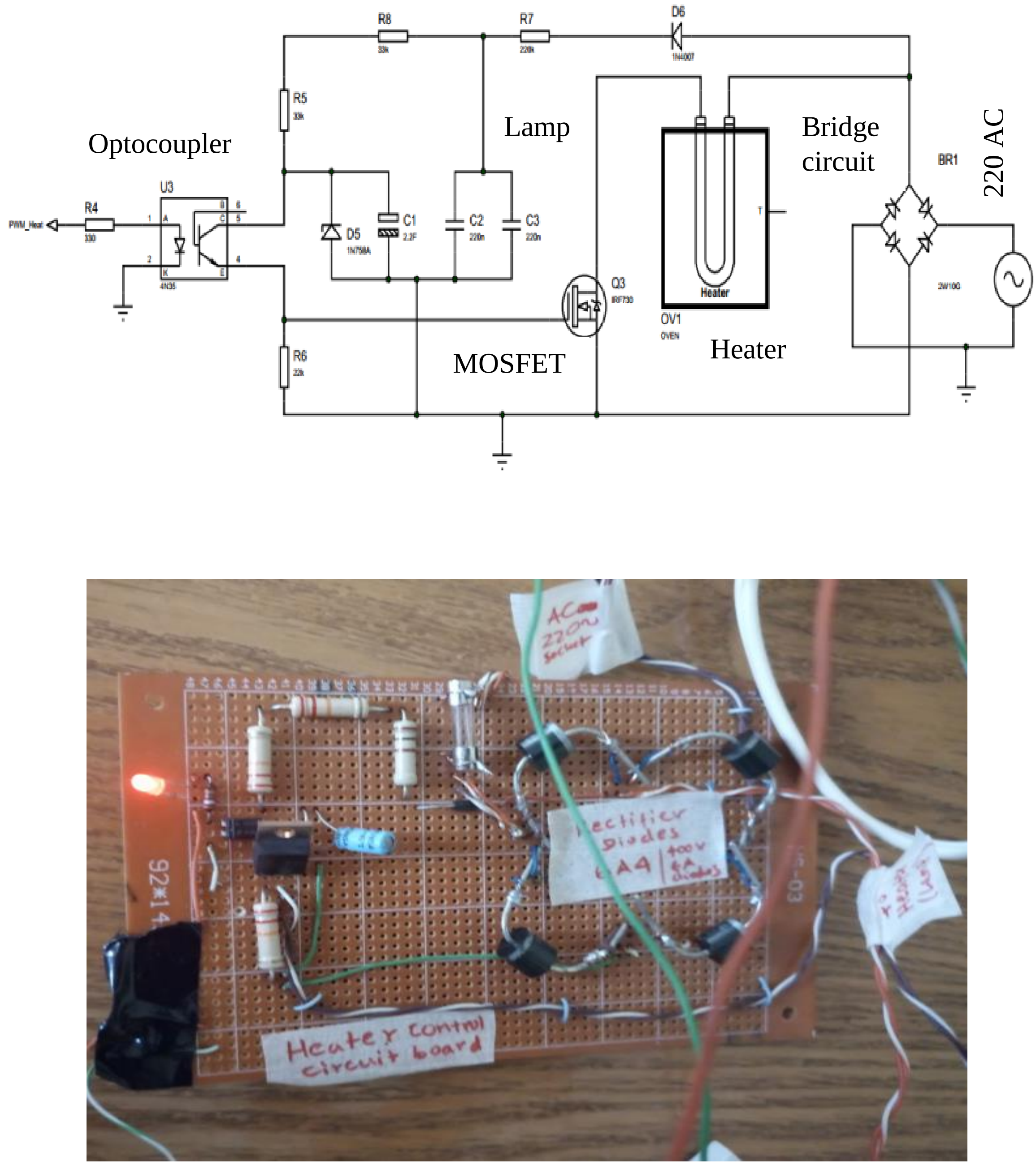
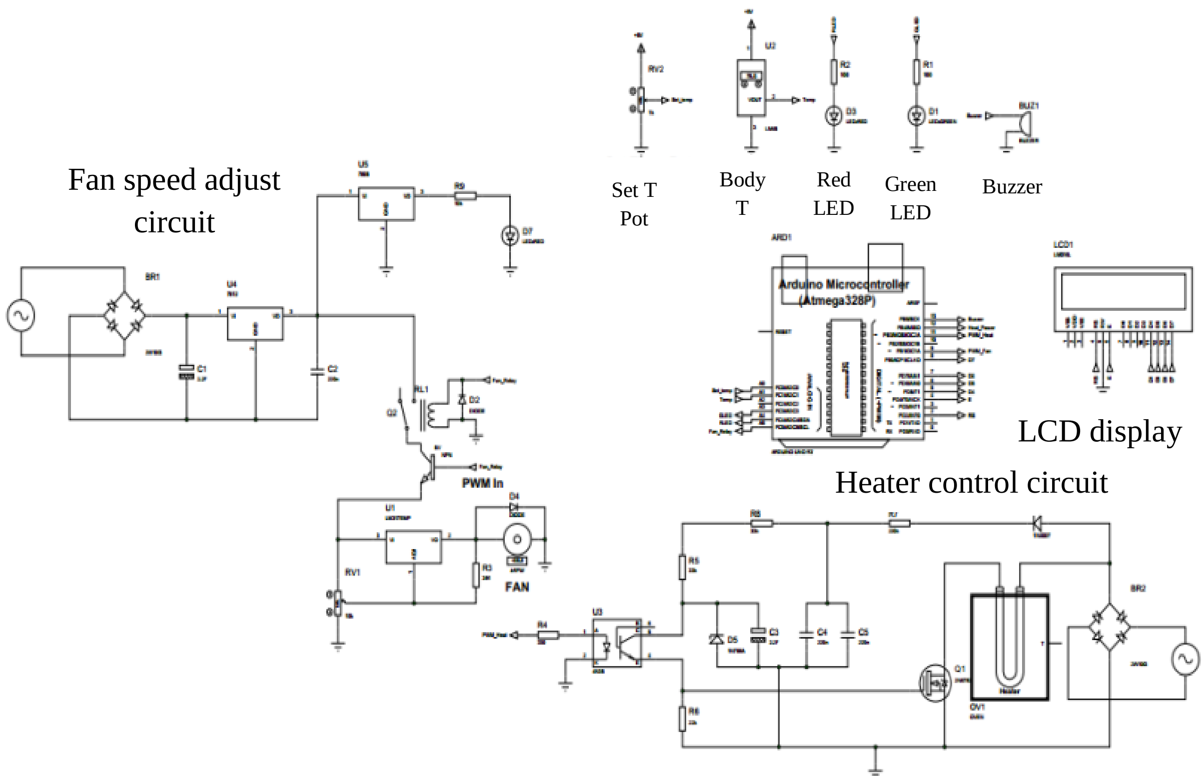


Figure 4-3: Heater control circuit board



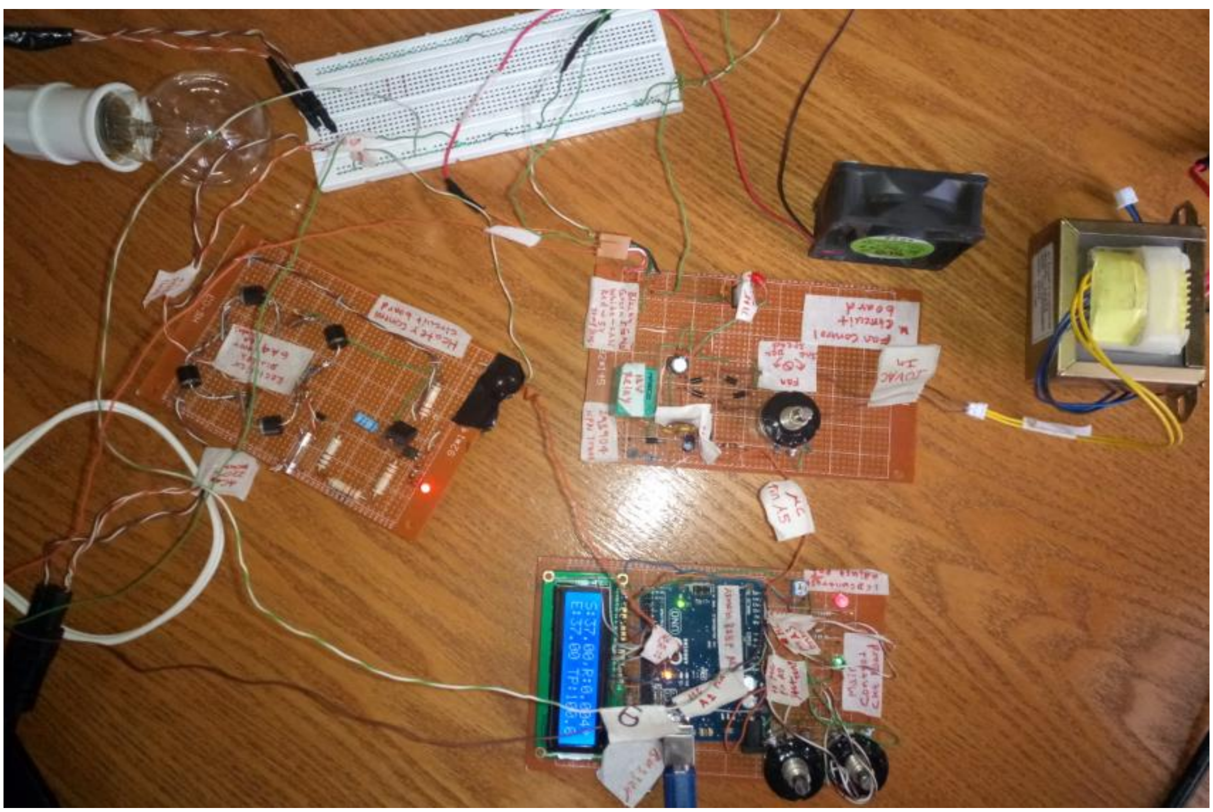


Figure 4-4: The three connected boards

In the prototype of the design, the whole power consumption which is the sum of heater circuit power, main control circuit power and fan circuit board power consumption is 16.7 Watt. This power consumption is satisfied from laptop in prototype testing but it will be obtained from rechargeable battery during the implementation of the design. In addition to its battery, the brightness of bulb is used to show the effect of the heater with variation of temperature sensor reading. This also replaced by heater on actual implementation of the design.

The construction of neonate bed chamber is made by transparent acrylic sheet. Acrylic is chosen because it is more resistant to thermal shock and to stresses caused by substantial temperature differences. Acrylic has many desirable electrical properties and continuous outdoor exposure during transportation has little effect on these properties [35]. It is a good insulator with surface resistivity higher than that of most plastics [35]. Acrylic will withstand exposure to blazing sun, extreme cold, sudden temperature changes, salt water spray and other harsh conditions [35]. It will not deteriorate after many years of service because of its inherent [35]. Nonabrasive soap or detergent and water can be used to clean acrylic sheet [36].

The compartment of electrical circuit is made by aluminum composite panel (ACP) material. ACP is formed by laminating a central core of thermoplastic material with an outer skin of aluminum sheet [37]. It guarantees good wind resistance and meets the stringent fire-protection requirements [38].

The three electrical circuit boards, fan circuit, heater circuit and main circuit, are found in 'L' shape box on the right and bottom side of the neonate bed. Figure 4-5 shows the constructed neonate warmer. On the bottom side of the bed, the fan, heater and main circuit boards are adjusted. On the right side of the neonate, inside the box, heater and fan are placed. The temperature sensor inlet also found in this side of the bed. The bed for the neonate is made by sponge and covered by synthetic leather which can easily be washed. The bed is constructed with pushcart and handle which can be pushed by any physician during transportation of the neonate from place to place.

Figure 4-5: The constructed mobile bed

Chapter 5 Conclusion and Recommendation

5.1 Conclusion

Preterm birth is a major cause of morbidity and mortality in developing countries like Ethiopia because preterm neonates lose their body heat rapidly and can't generate enough heat to keep their body temperature at normal state. These preterm neonates are exposed to much more unstable body temperature while they are transported to NICUs from delivery rooms and from clinics which give delivery services but do not have NICUs.

In this thesis project, we have designed and developed a device that prevents the mortality and morbidity of preterm neonates by measuring the preterm neonates' body temperature in real-time and providing efficient warming condition while they are being transported from one room (Delivery room) to another (NICU) for treatment. It also gives information to the physicians whether the preterm neonates' body temperature is in the normal condition or not. Our design helps to keep the preterm neonates body at normal temperature.

In the design process, several design ideas were proposed to meet the solution of the above problem and compared based on the criteria of safety, effectiveness, preterm neonate's comfort, functional time length and cost on the design matrix. Based on this comparison, the best design is selected to become our final design. The selected design uses a microcontroller, temperature sensors, fan and heater. The design is tested through proteus software before prototyping to ensure that each part will function properly. After testing on proteus software, a prototype is developed using Arduino microcontroller Atmega 328P and C program is used to write the code.

In the prototype of this design, the error is around 5 percent and the accuracy is 95 percent. This is because it was difficult to find the right temperature senor and the measured temperature sensor fluctuates for some time interval till it shows the correct reading.

The project is developed keeping in mind the medical conditions available in low resource settings. It can be effectively used by any physician and the components can be easily found and replaced.

5.2 Recommendation

Even though the result presented in this design brings potential solution for preterm neonates in low resource settings, it still needs some improvements for perfect temperature monitoring and controlling system. In the prototype testing of this design, the PWM of the heater doesn't adjust itself quickly according the requirement from the neonate's body temperature sensor through the microcontroller. So it needs advanced controlling mechanism which can give quick response for the fluctuation of the neonate's body temperature. The design also needs use of better temperature sensors which can be easily attached on the neonate's skin to get effective temperature reading from the neonate's body.

The whole function of the preterm neonate's body can be effectively monitored if the reading of electrocardiography and electroencephalography and pulse rate can be included in the design. These can help to control the whole body function while they are transported from place to place for further treatment.

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Appendix

```
#include <LiquidCrystal.h>

LiquidCrystallcd(2, 4, 5, 6, 7, 8); // RS E D0 D1 D2 D3

constintled_pin = A4;            // Green LED pin
constint led_pin2 = A3;            // Red LED pin
constintheater_pin = 11;          // Heater relay on pin
constintheater_relay_on_pin = 12; // Heater power on pin
constintfan_pin = A5;             // Fan connection pin
constintbuzzer_pin = 13;          // Buzzer out connection pin

constintnumReadings = 50;
voidreadValues();
float readings[numReadings];      // the readings from the analog input
float readings1[numReadings];     // the readings from the analog input
intreadIndex = 0;                 // the index of the current reading
float total = 0;                  // the running total
float average = 0;                // the average
float total1 = 0;                 // the running total
float average1 = 0;               // the average



floattempPWM = 100;  // Initial temp and fan values
floatsetTemp = 0, error = 0,  speedRead = 0, speedCtrl = 0, heat_pwm =0, speedPWM = 200, celsius = 0, setTempMean = 0, readTempMean = 0, value =0, tempMilVolt = 0, tempCelsius = 0; // Initialize to each variable to zero
constintPWM_step = 1, errorSet = 2;
```

```
intprevError = 0, currError = 0, meanError=0;

// Create characters

byte p0[8] = { B00000,B01010,B10101,B10001,B10001,B01010,B00100,B00000 }; // Create heart character for display

byte p1[8] = { B10000,B10000,B10000,B10000,B10000,B10000,B10000,B10000 }; // Create progress bar character for display

byte p2[8] = { B11000,B11000,B11000,B11000,B11000,B11000,B11000,B11000 }; // Create progress bar character for display

byte p3[8] = { B11100,B11100,B11100,B11100,B11100,B11100,B11100,B11100 }; // Create progress bar character for display

byte p4[8] = { B11110,B11110,B11110,B11110,B11110,B11110,B11110,B11110 }; // Create progress bar character for display

byte p5[8] = { B11111,B11111,B11111,B11111,B11111,B11111,B11111,B11111 }; // Create progress bar character for display

byte p6[8] = { B00010,B00101,B00101,B00010,B00000,B00000,B00000,B00000 }; // Create Degree celsius character for display


voidreset_all();


void setup() {

lcd.begin(16,2);   // Initialize 16x2 lcd

lcd.clear();       // Start by Clearing LCD  for character display

  //reset_all();

Serial.begin(9600);

for (intthisReading = 0; thisReading<numReadings; thisReading++) {

readings[thisReading] = 0;

readings1[thisReading] = 0;

  }


pinMode(buzzer_pin,OUTPUT);           // Set pin 7 to output mode

pinMode(heater_relay_on_pin,OUTPUT);   // Set pin 7 to output mode
```

```
pinMode(led_pin,OUTPUT);              // Set pin 6 to output mode
pinMode(led_pin2,OUTPUT);             // Set pin 6 to output mode
pinMode(fan_pin,OUTPUT);              // Set pin 6 to output mode
pinMode(heater_pin,OUTPUT);           // Set pin 6 to output mode

digitalWrite(heater_relay_on_pin,HIGH); // Begin by turning off heater

// Create heart character for display
lcd.createChar(1,p0);

// Create progress bar character for display
lcd.createChar(2,p1);
lcd.createChar(3,p2);
lcd.createChar(4,p3);
lcd.createChar(5,p4);
lcd.createChar(6,p5);
// Create degree celiscus character
lcd.createChar(7,p6);

// Show welcome display
lcd.setCursor(0,0);  lcd.write(1); lcd.setCursor(1,0); lcd.write(1); lcd.setCursor(2,0); lcd.write(1);
lcd.setCursor(3,0);  lcd.print("Welcome to");
lcd.setCursor(13,0);   lcd.write(1);   lcd.setCursor(14,0);   lcd.write(1);   lcd.setCursor(15,0);
lcd.write(1);
lcd.setCursor(0,1);  lcd.print("Neonate incubator");
delay(1500);             // Hold welcome display for 1.5 sec

lcd.clear();             // Clear LCD  for the next display
lcd.setCursor(0,0);      // Position LCD cursor at (0,0)
```

```
lcd.print("Loading...");  // Display System starting...

lcd.setCursor(0,1);       // Position LCD cursor at (0,1)
lcd.print("                ");

// Display progress bar
for(int i=0; i<16; i++)
  {
for(int j=2; j<7; j++)
    {
lcd.setCursor(i,1);
lcd.write(j);
delay(30);
    }
  }

lcd.clear();   // Clear LCD for the next txt display

setTemp = analogRead(A0);     // Read temprature setup
setTemp = map(setTemp,0,1023,0,60);

  //delay(50);

value = analogRead(A1);         // Read temprature setup  tempMilVolt = 0, tempCelsius
celsius =   value * 0.48828125;   //tempMilVolt = (value / 1024)*500;   milli-volt to degree celiciusconvertion factor

  //celsius = analogRead(A1);     // Read temprature setup
  //celsius = map(celsius,0,1023,0,60);
```

```
while(setTemp< 36.5 || setTemp> 37.5)  // setTemp< 36.5 &&setTemp> 37.5
      {

digitalWrite(led_pin,LOW);            // Turn ON Red LED for danger
digitalWrite(led_pin2,LOW);            // Turn OFF Green LED for danger

setTemp = analogRead(A0);     // Read temprature setup
setTemp = map(setTemp,0,1023,0,60);  // Set (Convert) temprature reading range from (0,1023) to (0,50)

lcd.setCursor(0,0);   // Position LCD cursor at (0,0)
lcd.print("Please Set Right Temp (37");
lcd.setCursor(25,0);  lcd.write(7);  lcd.setCursor(26,0);  lcd.print("C)");  // Display digreecelsius
lcd.setCursor(0,1);   // Position LCD cursor at (0,1)
lcd.print("Temp= ");
lcd.setCursor(5,1);
lcd.print(setTemp);
lcd.setCursor(10,1);  lcd.write(7);  lcd.setCursor(11,1);  lcd.print("C");
lcd.println("     ");

if(setTemp>= 36.5 &&setTemp<= 37.5)  // Check if temp is 37 setTemp>= 36.5 &&setTemp<= 37.5
       {
setTemp = 37;
lcd.clear();     // Clear LCD for the next txt display
lcd.print("    Temp set    "); lcd.setCursor(1,1);
lcd.print("  Successful!     ");
delay(500);
```

```
lcd.clear();
        }

}  // end while check set temp



}

//--------------------- Start forever loop --------------------------------------------------------------------
void loop() {

    // subtract the last reading:
readTempMean = readTempMean - readings1[readIndex];
    // read from the sensor:
readings1[readIndex] = analogRead(A1);  // Read temprature sensor
    // add the reading to the total:
readTempMean = readTempMean + readings1[readIndex];
value = readTempMean / numReadings;
celsius =  value * 0.48828125;  // milli-volt to degree celiciusconvertionfactortempMilVolt = (value / 1024)*500;

readIndex = readIndex + 1;
    // if we're at the end of the array...
if (readIndex>= numReadings) {
      // ...wrap around to the beginning:
readIndex = 0;
    }
//------  End mean value read of read temp -------------------------------------------------------------
display_setTemp(setTemp);     // Call display setTemp function to diplay set temp on LCD
```

```
display_tempRead(celsius);     // Call display_tempRead function to diplay heater temp read on LCD

display_tempPWM(tempPWM);       // Call display_tempPWM function to diplay temp control PWM value on LCD

Serial.println(celsius);

//------  End set temp Check --------------------------------------------------------------------------

if(setTemp>= 36.0 &&setTemp<= 38.0)  // setTemp>= 36.5 &&setTemp<= 37.5
{
error = setTemp - celsius; //if (error < 0) error = -1*error;
meanError = error;



//------  End Display calues ---------------------------------------------------------------------------

digitalWrite(heater_relay_on_pin,LOW);   // Turn on Heater power

if (meanError>errorSet)  // Check temp difference (error) is > 1, (Abnormal Range)
   // If heater temp < set temp by 10.5
    {
tempPWM = tempPWM + PWM_step;          // Increase heater PWM value
if(tempPWM> 255) tempPWM = 255;
analogWrite(heater_pin,tempPWM);       // Apply PWM value to increase
digitalWrite(led_pin,HIGH);            // Turn ON Red LED for danger
digitalWrite(led_pin2,LOW);            // Turn OFF Green LED for danger
```

```
digitalWrite(heater_relay_on_pin,LOW);  // Turn ON Heater power
digitalWrite(fan_pin,LOW);              // Turn OFF FAN
digitalWrite(buzzer_pin,HIGH);          // Turn ON Buzzer for danger
   }

else if (meanError>= -errorSet&&meanError<= errorSet)     // Check temp difference (error) is between -1 and 1, (Normal Range)
   // If heater temp (setTemp - 10.5) and (setTemp - 9.5)
   {
digitalWrite(heater_relay_on_pin,HIGH);   // Turn OFF Heater power
digitalWrite(led_pin,LOW);         // Turn OFF Red LED b/c it is Normal range
digitalWrite(led_pin2,HIGH);       // Turn ON Green LED b/c it is Normal range
digitalWrite(fan_pin,HIGH);        // Turn ON Green LED b/c it is Normal range
digitalWrite(buzzer_pin,LOW);      // Turn OFF Buzzer for danger
tempPWM = 75;
analogWrite(heater_pin,tempPWM);  // Apply PWM value to increase
   }
else if (error < -errorSet)  // Check temp difference (error) < -1, (Abnormal Range)
   {

tempPWM = tempPWM - PWM_step;                 // Decrease heater PWM value
if(tempPWM< 0) tempPWM = 0;
analogWrite(heater_pin,tempPWM);        // Apply PWM value to increase
digitalWrite(led_pin,HIGH);             // Turn ON LED for danger
digitalWrite(led_pin2,LOW);             // Turn ON LED2 for danger
digitalWrite(heater_relay_on_pin,LOW);  // Turn ON Heater power
digitalWrite(fan_pin,LOW);              // Turn OFF FAN
digitalWrite(buzzer_pin,HIGH);          // Turn ON Buzzer LED for danger
```

```
  }
} // end if 2

}

voiddisplay_setTemp(float sTempVal)
{
lcd.setCursor(0,0);
lcd.print("S:");
lcd.setCursor(2,0);
lcd.print(sTempVal);
lcd.setCursor(7,0);
lcd.print(",");
}

voiddisplay_tempRead(float rTemp)
{
lcd.setCursor(8,0);
lcd.print("R:");
lcd.setCursor(10,0);
lcd.print(rTemp);
lcd.setCursor(15,0);
lcd.write(7);
lcd.setCursor(16,0);
lcd.print("C");
}

voiddisplay_tempPWM(float heat)
```

```
{
lcd.setCursor(0,1);
lcd.print("E:");
lcd.setCursor(2,1);
lcd.print(error);
lcd.setCursor(8,1);
lcd.print("TP:");
lcd.setCursor(11,1);
heat_pwm = (heat/255)*100;
lcd.print(heat_pwm);
lcd.setCursor(16,1);
lcd.print("%");
}

voiddisplay_speedPWM(float spdPWM)
{
lcd.setCursor(21,1);
lcd.print("SPWM:");
lcd.setCursor(26,1);
spdPWM = (spdPWM/255)*100;
lcd.print(spdPWM);
lcd.setCursor(31,1);
lcd.print("%");
}

voidreset_all()
{
digitalWrite(buzzer_pin,LOW);          // Begin by turning off Buzzer pin
```

```
digitalWrite(heater_pin,LOW);          // Begin by turning off heater pin
digitalWrite(heater_relay_on_pin,LOW); // Begin by turning off heater relay pin
digitalWrite(led_pin,LOW);             // Begin by turning off green LED pin
digitalWrite(led_pin2,LOW);            // Begin by turning off red LED pin
digitalWrite(fan_pin,LOW);             // Begin by turning off fan pin

}

voidcheckSetTemp(float setTempVal)
{
if(setTempVal == 37)  // Check if temp is 37
   {
lcd.clear();     // Clear LCD for the next txt display
lcd.print("    Temp set    "); lcd.setCursor(1,1);
lcd.print("  Successful!   ");
delay(1500);
lcd.clear();
   }
}
```