Faculty of Engineering

Medical Wristband Body Temperature Monitor

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Abstract

A brief overview of the importance of measuring body temperature and types of body temperature measuring devices are given to gain an understanding of the context of the problem. The problem is the need for a non-invasive body temperature measuring device that can accurately measure core body temperature, whilst being simple, low-cost, lightweight, and energy-efficient. High-level objectives are given that will be pursued in solving the problem.

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Chapter 1 Introduction

1.1 Purpose of document

This report covers the context in which a problem exists and also why it is important to address the problem by providing a short background on devices that measures body temperature, the use thereof, and the working of these devices. Some background information is then used to provide a summary of the problem at hand. A possible solution is then shortly discussed, followed by some high-level objectives that will be pursued in an attempt to solve this problem. Anticipated benefits of the solution, technical requirements, scope of the project, and project deliverables are given to provide more context of this project.

1.2 Background

Body temperature can be defined as the measure of how well the human body can get rid of and generate heat. Body temperature is needed to sustain and promote human life. The measurement of body temperature plays an important role in our everyday life (especially in the pandemic we find our-self in) since several diseases are characterised by a change in body temperature. Some body temperature measuring devices, such as the clinical thermometer, which is commonly used domestically and in hospitals, must be placed underneath one's tongue or under the armpit. This proves to be unhygienic when these measuring devices are not properly cleaned and can also cause some annoyance for certain people. The need for non-invasive body temperature measuring equipment exists, that can fast and effectively determine body temperature on the move. Mobility will ensure that body temperature readings are always available, anywhere.

Rotational motions and constant internal vibrations in molecules generate thermal energy or heat. Temperature is therefore a measure of the average thermal energy of molecular motions. Biochemical processes take place inside living cells that contain molecules and are greatly influenced by body temperature [2]. These biochemical processes are known as metabolism. Humans are homeothermic and body temperature is regulated at about 37°C ± 1°C [7]. The body needs to maintain its temperature at a certain level to support and stimulate its metabolic activities. Both temperature statuses, hyperthermia (too high) or hypothermia (too low) can alter metabolic activities, cause tissue damage and disturb organic functions. Hence, it is important to examine and monitor body temperature to hunt for signs of diseases that are characterised by a change in body temperature. Body temperature measurements allow doctors and other medical practitioners to analyze the effectiveness of the prescribed treatment. Table 1.1 shows both extremes of body temperature and some associated effects at certain temperatures.

Table 1.1: *Body temperature effects*[2]

Temperature	Effect
24-28°C	Mostly death
29-33°C	Sleepiness, slow heartbeat, moderate to severe confusion, unresponsive to stimulus.
34-35°C	Bluish/Grayness of the skin, intense shivering, numbness and some confusion.
36°C	Mild to moderate shivering.
37°C	Normal temperature
38-40°C	Dehydration, headache, vomiting and severe sweating.
41-42°C	Confusion, fainting, very fast heart rate and high/low blood pressure.
43°C	Brain damage, normally death.

Various types of body temperature measuring devices already exist, some of the most popular domestic-used devices are listed below, each followed by a short description:

- Oral Thermometer:
  Most oral thermometers are digital with a housing made out of plastic. This is an invasive device that must be placed under the tongue for a short while allowing it to measure body temperature. The oral thermometer uses thermistor resistance that varies with temperature as sensing element. In many cases, the user will be alerted when the reading is completed.

- Tympanic Thermometer:
  Tympanic Thermometers are minimally invasive since it is placed inside the ear canal to take body temperature readings. This type of device measures the natural emission of infrared thermal radiation from the tympanic membrane. This digital device has a cone shape designed to fit into an ear.

- Mercury-in-glass/ Alcohol-in-glass Thermometer:
  This device measures oral, rectal, or armpit body temperature through the thermal expansion of ethanol/mercury. These types of devices are made of glass and the thermal expansion of the ethanol/mercury caused by heat must be noted by the user when taking a reading.

- Infrared Thermometer:
  This is a non-invasive device that measures thermal radiation (infrared) emitted from the forehead and skin to deduce body temperature. The infrared thermometer uses a pyroelectric sensor to measure temperature. Infrared thermometers are digital and the user could be alerted when a reading is abnormal.

The devices listed have their own advantages and disadvantages. According to [8], oral thermometers are most accurate for children over 3 years of age and adults. The drawback is that, as mentioned earlier, if the device is not cleaned properly it may be unhygienic. The article also mentions that tympanic thermometers provide fast and accurate readings but objects such as earwax and improper positioning may distort results. The Mercury-/Alcohol-in glass thermometers are not digital, the user must constantly look at the expansion of the liquid to determine the reading. Infrared thermometers provide quick readings contactless. However, it is believed that these infrared thermometers are not truly as accurate as the rest since external factors, such as direct sunlight and indoor heating, may affect the readings [8].

Throughout this section, mentions of invasive and non-invasive methods were made. These are the two main methods to measure body temperature — by measuring core (deep tissue, invasive) temperature and surface (skin, non-invasive) temperature. Invasive temperature measurements can be taken through the oral cavity, ear canal, and rectum, whilst non-invasive readings are made on the skin surface. In many cases invasive methods cannot be used, such as when someone is unconscious, confused, or sneezing repeatedly, then the oral measurement method is unsuitable. When someone has a middle ear infection or an obstruction in their ear by wax, the ear method is of no use. Non-invasive methods can easily be affected by external factors such as sunlight and indoor heating/cooling, as mentioned previously.

1.3 Problem Statement

From the previous section, it is clear that a non-invasive body temperature measuring device is needed that can measure core body temperature, without the readings getting affected by external factors, whilst being comfortable.

1.4 Hypothesis

A medical wristband that can measure body temperature will be designed and constructed. This allows end-users to wear the device on their wrist, and to see his or her body temperature that is measured and displayed by the wristband.

1.5 Project Objective

1.5.1 Primary Objective

The primary objective of this project is to design an accurate body temperature measuring device that can be worn as a wristband. The device should measure one's body temperature without the readings getting affected by external factors. The device will predict core body temperature instead of just measuring surface (skin) temperature.

Since the device will predict core body temperature, a thermal equivalent circuit model will be used to measure core body temperature with a skin-attachable sensor and experimental investigations will be used to further improve this model. Improvements will lead to more accurate readings. A low-level example of a thermal equivalent circuit model can be seen in Figure 1.1.

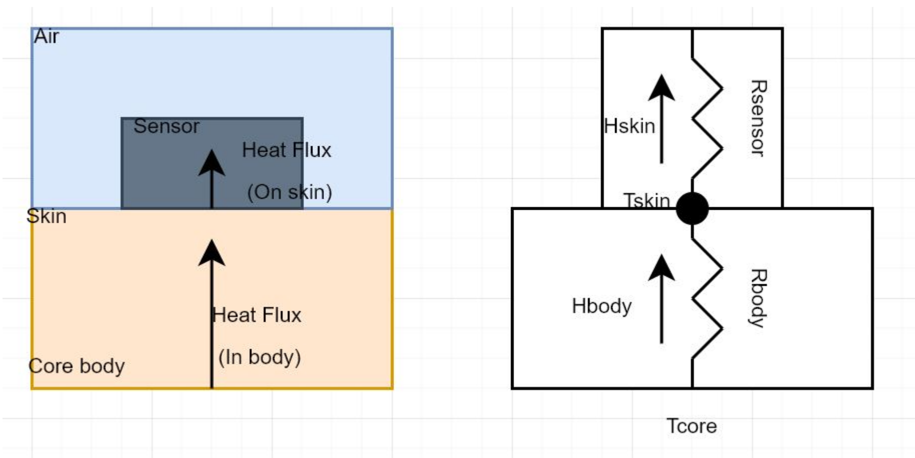

Figure 1.1: Low level model and thermal equivalent circuit.

1.5.2 Secondary Objective

The device will be able to measure body temperature, this must also be displayed to the user of the wristband. Therefore, the secondary objective is to implement a Human-Machine Interface (HMI).

1.6 Anticipated Benefits of Solution

The device in the form of a wristband will make the process of measuring body temperature easier and more efficient since the wristband can be comfortably worn throughout the day or night providing continuous readings. These readings are updated by the device on a set interval or on-demand, whilst always displaying the most recent reading. Users will be alerted when the temperature is too high or low so that treatment can be undergone right away. This will also be a low-cost, yet reliable build.

1.7 Technical Requirements

1.7.1 Requirements

The requirements are listed below:

1. Lightweight. The final wristband with the measuring device and the HMI shall be lightweight. This supports the need for a comfortable device.
2. Low energy usage. Since the end product will be in the form of a wristband, it will be portable. This means that the measuring device will be battery-powered. Low energy usage shall extend the battery life of the device.
3. Cheap. The low-cost aspect of the end product will ensure that the wristband can be widely used by anyone with the need.
4. Simple. The device will measure body temperature, show the measured temperature and alert the user when the temperature is outside the set limits.
5. Accurate. The device shall deliver readings with an accuracy of ± 0.5°C to the user of the device.
6. The measuring range of the device shall be from 30°C to 40°C, since these temperatures are roughly the limits any living person will achieve.
7. The device shall operate in atmospheric temperatures ranging from -5°C to 45°C, making the body temperature measuring device operational in the summer and winter.

1.7.2 Scope Definition

The scope of the project is to design and implement a body temperature measuring device that can report back a measured reading. Therefore, the sensing element, power supply or battery, and HMI components will not be re-designed, existing components will be used and placed on a Printed Circuit Board (PCB) to make the device small and compact. The wristband itself will not be part of the design, although this can be 3D printed.

1.8 Deliverables

A device that can measure and display body temperature on the move by placing the device on the wrist will be delivered. This device will be mounted on a wristband that can fit around one's arm at the wrist. Circuit design and PCB layout, together with an enhanced thermal equivalent circuit will also be provided.

1.9 Concluding Remarks

This section explained the importance of measuring body temperature as it is an indication of a person's physical health status. Some requirements are given, showing what will be incorporated in the final product. The scope definition ensures that all the requirements are reached without doing unnecessary work.

Chapter 2 Literature Study

This chapter contains a literature study on the most relevant techniques, equipment, and technologies related to this project. Firstly a high-level block diagram of the proposed solution is given whereafter the relevant technologies that are commonly available within the scope of the proposed solution are discussed. The different types of temperature transducers, display, and battery technologies related to this project are reviewed and some important methods to measure core body temperature from skin temperatures are discussed.

2.1 High-level block diagram

In this section a high-level block diagram of the proposed solution is given. The diagram is shown in Figure 2.1 and consists of 4 main functional units.

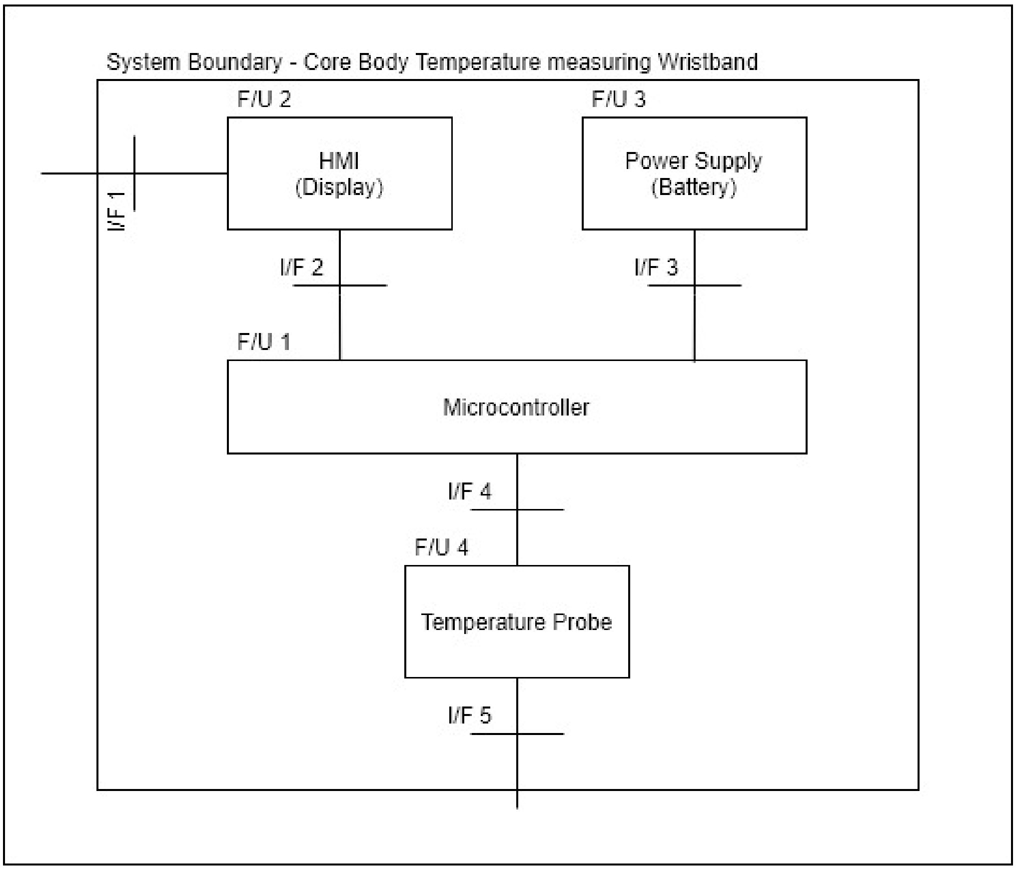

Figure 2.1: High level block diagram of proposed solution

The functional units of the proposed solution are briefly discussed in Table 2.1.

Table 2.1: *High-level functional unit description*

Description	**Functional Unit**
Analogue to Digital conversion, Processing and Analysation of measurements, estimation of core body temperature.	Microcontroller
Display the measured temperature.	HMI
Deliver power to the system.	Power Supply
Measure skin temperature, configuration will allow the microcontroller to estimate core body temperature.	Temperature Probe

2.2 Classification of Body Temperature

Body temperature measuring dates back to ancient times when physicians used their hands to estimate body temperature by noting the difference in temperature between the head and foot of a patient. As society modernised, more information and technology became available, leading to instruments that can predict and measure body temperature. In practice, the measurement of body temperature is categorised in three distinct types referred to as core body temperature, surface body temperature, and basal body temperature [2]. The type is determined by considering measurement position. Core body temperature refers to the deep tissue of the body and is the operating temperature of all inner organs. Core body temperature is measured using invasive methods. Surface body temperature is measured on the skin and can be used to estimate core body temperature. Basal body temperature is the lowest body temperature taken right after waking up and before any physical activity and is mostly used to determine and predict ovulation in women [9]. There are various positions available to measure body temperatures such as sublingual, esophagus, bladder, rectum, and digestive tract for the measurement of core body temperature, and axilla, groin, neck, and wrist for surface body temperature.

Surface body temperature can easily be measured non-invasively, but can also be susceptible to environmental factors. Since there is a need for a non-invasive body temperature device, the rest of the literature study will focus on surface body temperature measuring techniques, sensing elements, and how to predict core body temperature from surface body temperature.

2.3 Temperature sensing elements

Temperature sensing elements, or from now on referred to as transducers, convert heat energy or temperature into other forms of energy [2]. The other forms of energy can then be processed and the temperature can be made visible on a legible temperature scale. This section discusses several temperature transducers that can be used to measure core body temperature.

2.3.1 Thermistor

Thermistors are semiconductor-resistive temperature transducers where the resistance of the material changes as the temperature changes [10]. There are two types of thermistors available, the Negative Temperature Coefficient (NTC) thermistor and the Positive Temperature Coefficient (PTC) thermistor [11]. The resistance of an NTC thermistor decreases as the temperature increases and consequently the resistance of a PTC transducer increases as the temperature increases. NTC thermistors are commonly used in body temperature measurements since it has good linearity in the range of body temperature, whereas the PTC thermistor has poor sensitivity in the range of body temperature and are mostly used for higher temperature measurements [2]. The conversion from resistance to temperature is usually given in the datasheet of the specific thermistor.

2.3.2 Thermocouple

Thermocouples have two different metal wires connected together as a junction and when the temperature of the junction is changed, the junction output voltage varies with this change [12]. Therefore, the Seebeck effect is used as a thermoelectric transducer [2]. The Seeback effect is the phenomenon in which a temperature difference of two dissimilar conductors connected together produces a voltage gradient. This voltage can then be measured and converted to temperature. Several types of thermocouples are available and are classified according to the material used and the different types are differentiated by designated letters [10]. Some of the most commonly used thermocouples are shown in Table 2.2.

Table 2.2: *Thermocouple types [1]*

Designated letter	**Conductor Alloys (+/-)**	**Sensing Range (°C)**
E	Nickel Chromium / Constantan	-40 to 900
J	Iron / Constantan	-180 to 800
K	Nickel Chromium / Nickel Aluminium	-180 to 1300
N	Nicrosil / Nisil	-270 to 1300
T	Copper / Constantan	-250 to 400
R/S	Copper / Copper Nickel Compensating	-50 to 1750
B	Platinum Rhodium	0 to 1820

Most applications that use a thermocouple as a temperature transducer, require precise amplification since the output voltage is quite small. This adds circuitry to the measurement device and is not ideal for smaller-sized projects.

2.3.3 Resistive Temperature Detector

Resistive Temperature Detectors or RTDs work on the same principle as thermistors, where the varied resistance of the metal is measured when there is a temperature change. The most common and accurate material used to make RTDs is platinum [10]. The reason for this is that platinum RTDs offer a nearly linear response to temperature changes, repeatable responses, a wide temperature range, and they are accurate and stable. RTD configurations can be two-/three-/four-wire and is shown in Figure 2.2. An excitation current flows through the RTD and the voltage across the RTD is measured.

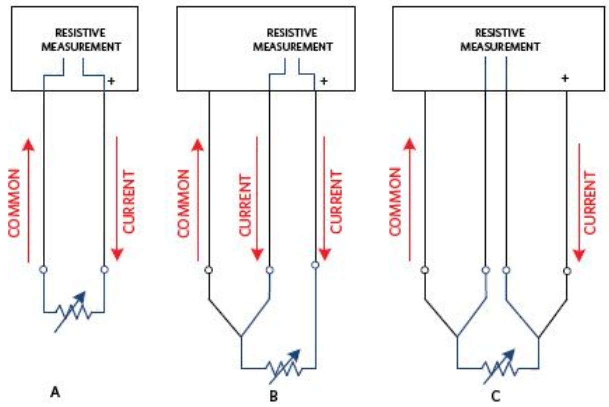

Figure 2.2: RTD configurations [1]

RTD thermal transducers respond slower than thermocouples to changes in temperature [10].

2.3.4 Semiconductor based Integrated Circuit

The semiconductor sensor in an integrated circuit (IC) contains many types of circuitry on one chip [12]. Semiconductor-based IC measures temperature by using the physical properties of a transistor [10]. The collector current and base-emitter voltage of a bipolar junction transistor (BJT) is used to calculate the measured temperature. The PN junction is therefore used as a temperature transducer. The forward voltage drop across a forward-conducting PN junction of a transistor at constant forward-bias current exhibits linear temperature dependence over a wide temperature range [2]. Temperature transducers based on this principle can be realised by applying a square-wave current to a PN junction [13] or by using two matched devices operating at different currents.

2.3.5 Infrared

The temperature of an object can be measured by the thermal radiation power emitted from the object with a temperature above zero. The infrared energy emitted from an object is proportional to its temperature. This method can be used to measure body temperature since the peak of the thermal radiation emitted from a human body lies in the far-infrared region [2]. The infrared type temperature transducer can make temperature measurements contactless and also on moving objects. Most infrared temperature transducers use a pyroelectric sensor to measure temperature.

2.4 Techniques for Non-invasive CBT measurements

Several non-invasive methods have been developed to measure core body temperature since the early 1970s [2]. The reason for this is that some core body temperature measuring techniques are unsatisfactory for continuous use and may cause discomfort to the patient [14]. Furthermore, some invasive measurements can induce complications [15]. The working of the developed methods is discussed next.

2.4.1 Zero-heat-flow Method

The zero-heat-flow method is used to estimate core body temperature in a non-invasive manner. The estimation is made by measuring the temperature on the skin surface with a probe that consists out of two thermistors, a thin-film heater element, and a piece of nylon used as a thermal insulator. These components are encapsulated by silicone rubber and the structure can be seen in Figure 2.3.

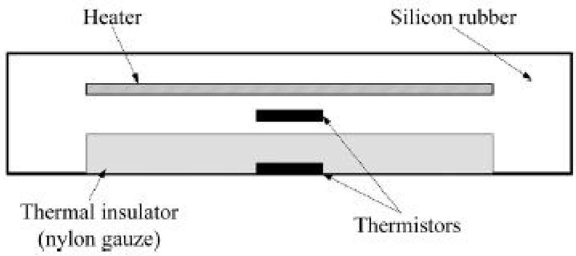

Figure 2.3: Zero-heat-flow structure[2]

The heater element is used to reduce ambient effects on measurements [4]. The method is based on heat or thermal insulation to reduce heat loss from the skin. Two matched thermistors are used to detect the temperature on both sides of the insulating layer and these temperatures are then compared. The temperature difference between them is used to control the heater current in such a way that there is no temperature gradient across the insulating layer, therefore no heat flowing through this layer [14]. As long as the condition of zero-heat-flow is satisfied, the probe can be seen as an ideal thermal insulator, and heat loss from the skin is prevented. After a while, the skin temperature will be in equilibrium with deep tissue temperature and the lower thermistor that is in contact with the skin may be used to measure skin temperature [14].

Since a heater element is present in this method, it requires a substantial amount of power. This, together with the relatively big size is not ideal for low-energy, smaller-sized projects.

2.4.2 Dual-heat-flux Method

In response to the zero-heat-flow method mentioned above that needs a heater element, the dual-heal-flux method was developed that works without a heating element [3]. The measurement probe is built structurally to form two different thermal pathways, hence the name dual-heat-flux. Temperature is measured by temperature transducers at the end of each channel. The structural layout of this method is shown in Figure 2.4.

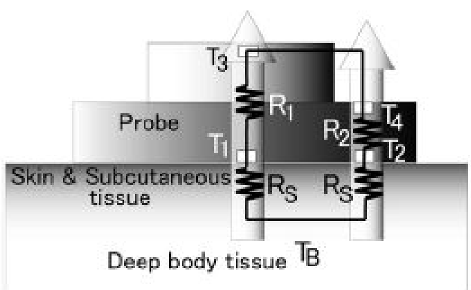

Figure 2.4: Dual-heat-flux structure[3]

From the schematic diagram above, the two channels of heat flow and the equivalent circuit can be seen. The skin is covered by two kinds of heat insulators that have different thermal resistances, R_1 and R_2, R_s is the thermal resistance of the subcutaneous tissues and skin, T_1 and T_2 are the skin temperatures under the insulator, and T_3 and T_4 are the upper temperatures at the surface of the insulator [2]. T_B is the core body temperature that needs to be measured. Kitamura et al. [3] derived the following equation to estimate core body temperature by assuming that R_s of both channels are identical:

$$T_B = T_1 + \frac{(T_1 - T_2)(T_1 - T_3)}{K(T_2 - T_4)(T_2 - T_4)} \tag{2.1}$$

K is the ratio of thermal resistance and can be determined from Equation 2.1 by rearranging the terms and conducting experimental calibration in a water bath:

$$K = \frac{(T_B - T_2)(T_1 - T_3)}{(T_B - T_1)(T_2 - T_4)} \tag{2.2}$$

where, T_B can be set to the preset water temperature.

This method has shown promising results, however, underlying skin anatomy and ergonomics still remain an issue [16]. In this method R_s of both channels are presumed to be identical since two insulators are placed close to each other, resulting in K not being influenced by R_s. However, Feng et al. [17] found that K is a function of the thickness of the skin or body, and R_s cannot be cancelled out once R_s changes. R_s will change with different skin types, colours, and thicknesses. Feng et al. [17] also revealed that the dual-heat-flux method has a long measurement time and systems based on this method are relatively large.

2.4.3 Thermal equivalent circuit model

The dual-heat-flux method does not take ambient conditions into consideration and heat flux from core body temperature may uncontrollably leak directly into the ambient environment instead of being measured by the transducers mentioned in the dual-heat-flux method [4]. Another method to measure core body temperature from the skin surface is to use the thermal equivalent circuit model to estimate core body temperature with a skin-attachable probe.

The thermal equivalent circuit for a skin-attachable sensor for the core body temperature estimation model was first developed by Fox et al. [18]. An amended thermal equivalent circuit can be seen in Figure 1.1 of this report. The core body temperature (T_{core}) is estimated by the following:

$$T_{core} = T_{skin} + (R_{body} \times H_{skin}) \tag{2.3}$$

where the skin surface temperature, the measured heat flux and the thermal resistance of the body are denoted by T_{skin}, H_{skin} and R_{body} respectively. Matsunaga et al. [4] developed an improved thermal equivalent circuit model which takes the uncontrolled heat flux leak to the ambient environment, and external convection changes into consideration. The improved thermal equivalent circuit is shown in Figure 2.5.

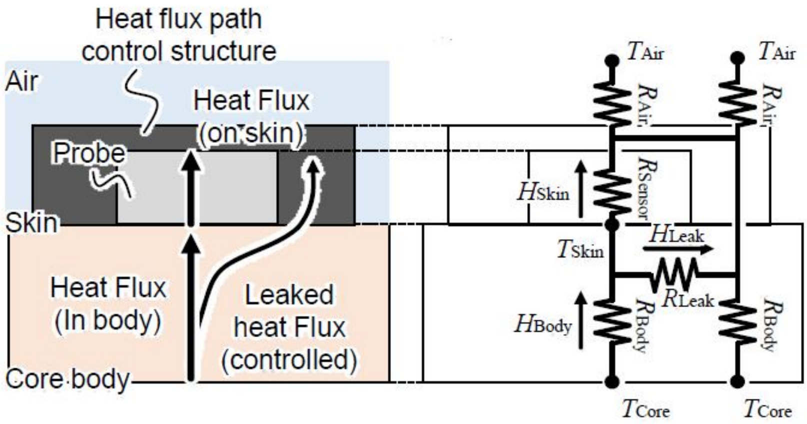

Figure 2.5: Improved thermal equivalent model [4]

In this figure, the thermal resistance of the probe, heat flux in the body, the ambient temperature, and thermal resistance to ambient air are denoted by R_{sensor}, H_{body}, T_{air} and R_{air} respectively. R_{leak} and H_{leak} denote the thermal resistance of the leakage path and the leaked heat flux. Matsunaga et al. [4] then gives the core body temperature (T_{core}) as the following:

$$T_{core} = T_{skin} + (R_{body} \times \alpha H_{skin}) \tag{2.4}$$

α is the calibration coefficient and is given by:

$$\alpha = \frac{(H_{skin} + H_{leak})}{H_{skin}} \tag{2.5}$$

By using H_{skin} and H_{leak} together with Kirchhoff's first and second laws, α can be rewritten as a function of thermal resistance:

$$\alpha = 1 + \frac{R_{sensor}}{R_{leak}} \tag{2.6}$$

From Equation 2.6 it is clear that α does not depend on R_{air} which means that the calibration coefficient does not change by changes in ambient conditions, and consequently, estimation errors do not occur. Through this process, Matsunaga et al. [4] considered R_{body} and R_{leak} as constant since they mainly depend on the thickness of the human body at the point of measuring. R_{sensor} is also constant. To control the heat flux path, the probe is wrapped with a highly conductive material to ensure that the leaked heat flux is passing through the thermally conductive material.

It is clear that the thermal resistance of the body is still needed to use this method. When using an average value for R_{body} estimation errors may occur that impacts the accuracy of the method. It is also generally quite difficult to obtain the thermal resistance of the leakage path.

2.4.4 Statistical Estimation

This method estimates core body temperature from skin temperatures by following a technique that is completely different from the previous methods. Kwak et al. [5] proposed a statistical estimation of core body temperature from skin temperature. In this method, the central limit theorem of statistics is used to overcome the problems faced when using a skin-attachable sensor to measure core body temperature. One of the major problems that are faced is that skin temperature is affected by external conditions such as wind and ambient temperature. The central limit theorem states that if there is a population with a mean and a standard distribution and many samples are taken from the population, the distribution of the sample means will be approximately normally distributed [19]. In other words, arbitrary distributions are normally distributed as the number of samples increases. Kwak et al. [5] uses this theorem to obtain a normal distribution of skin temperature and core body temperature and map each normal distribution to each other.

This method requires a lot of data or samples to increase its accuracy. Therefore, many measurements should be made on the ambient temperature, the skin temperature and the core body temperature. After a generous amount of data is gathered, the statistical model can be build. The following steps are followed to build the statistical model [5]:

1. Draw boxplot:
   A boxplot is a standard way of showing the distribution of data by providing a five number summary(minimum, first quartile, median, third quartile, and maximum). Outliers from the data model based on core body temperature are excluded since some measurements may be erroneous.

2. Draw histograms:
   A histogram of skin temperature and core body temperature should be drawn respectively. The histograms are then used to find the fitting Gaussian functions for skin temperature and core body temperature. The Gaussian functions for skin temperature and core body temperature are respectively:

$$skin\_gauss(x) = a_1 \times \exp[-(\frac{x-a_2}{a_3})^2] \tag{2.7}$$

$$body\_gauss(y) = b_1 \times \exp[-(\frac{y-b_2}{b_3})^2] \tag{2.8}$$

   where x is a random variable for skin temperature, y a random variable for core body temperature, a_1, b_1 the amplitudes, a_2, b_2 the centroids and a_3, b_3 the peak widths.

3. Map the Gaussian function of skin temperature to the Gaussian function of core body temperature:
   The Gaussian function of skin temperature is firstly mapped to a standard normal distribution and then the standard normal distribution is mapped to the Gaussian function of core body temperature. A relevant example of the mapping is shown in Figure 2.6.

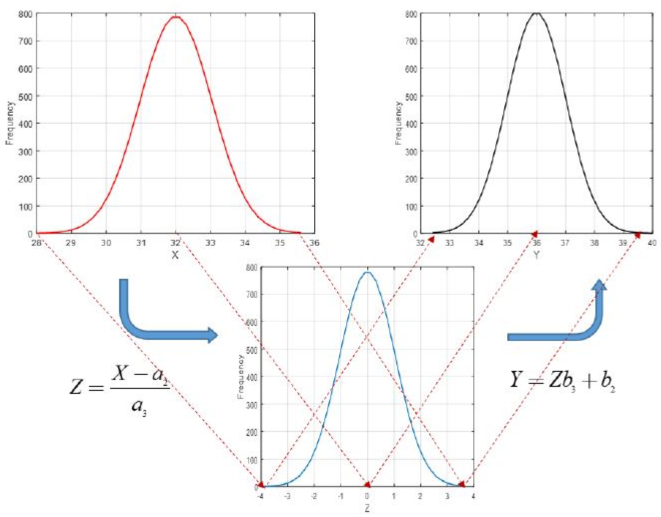

Figure 2.6: Mapping of Gaussian functions [5]

where the corresponding formula is given by:

$$Y = b_3\left(\frac{X - a_2}{a_3}\right) + b_2 \tag{2.9}$$

Kwak et al. [5] concluded that the statistical method estimates core body temperature reliably and that the estimated core body temperatures are within the margin of error tolerance of actual thermometers. The main drawback of this method is that a lot of data or samples are needed to build a statistical model that will deliver reliable results.

2.5 Display Technologies

Many display technologies and modules coexist and compete for their share in the market [6]. The term display in this context is referring to an output device that can exhibit, show or project information to visually communicate with a user. This section will focus on the most widely used display technologies that are available for low power consumption applications.

Fernández et al. [6] reviewed the display technologies available, focusing on the power consumption of each technology. The following figure shows the power consumption density of the various display technologies:

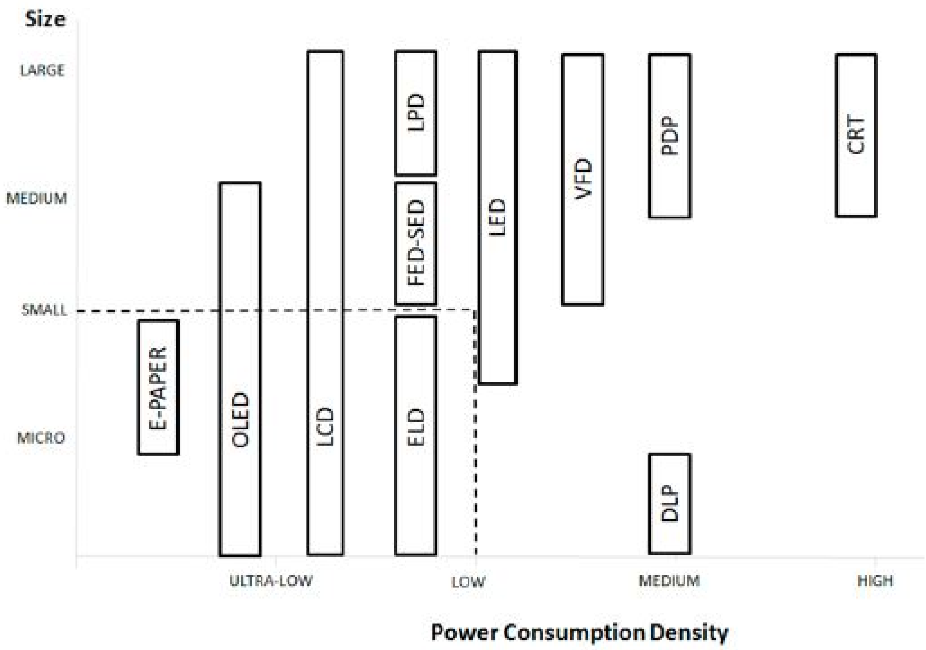

Figure 2.7: Power Consumption Density of Display Technologies [6]

From Figure 2.7 the technologies that consume low, and ultra-low power can be determined. These display technologies that are commonly used will be briefly discussed next.

2.5.1 E-PAPER

E-PAPER (Electronic paper) is a display technology designed to mimic the appearance of ordinary in on paper [20]. Millions of microcapsules containing negatively charged black and positively charged white particles suspended in a clear liquid are the composition of the display [6]. This technology does not require a backlight to illuminate its pixels and is made from a flexible material that requires ultra-low power to operate. E-Paper is also easier to read at an angle compared to flat-screen monitors.

2.5.2 LPD

LPD (Laser Phosphor Display) is a breakthrough phosphor screen technology that is powered by a laser engine. LPD uses solid state lasers to excite phosphors, and as the lasers scan the surface, the phosphors emit red, green, and blue colours that generate high-resolution images [21]. The lasers modulate by turning on and off for each pixel to create an image.

2.5.3 LED

LED (Light-Emitting Diodes) are opto-semiconductors that convert electrical energy into light energy. This technology emits light by applying a voltage to an inorganic semiconductor [22]. An electronic display screen has many independent arranged pixels and full colour LED displays select red, green, and blue as primary colours where each pixel consist of an LED [23]. The colour of the LED is realised by controlling the LED brightness i.e. the current through the semiconductor.

2.5.4 OLED

An OLED (Organic Light-Emitting Display) is an LED in which the emissive electroluminescent layer is an organic compound film, hence, it is a solid-state device made of a thin, carbon-based semiconductor layer that emits light when an electric current is applied [22].

2.5.5 LCD

LCD (Liquid Crystal Display) technology consists of an array of tiny segments that can be manipulated, using polarization of lights, to present information. This display technology belongs to the non-emissive display category, meaning that a backlight is included in the design, which in turn means that slightly more power than OLED and E-PAPER is consumed [6].

2.5.6 ELD

ELD (Electroluminescent Display) technology uses a strong electric field to take advantage of the light-emission phenomenon [6]. ELDs consists of a solid state thin phosphor film and insulator stack deposited on a glass substrate that is driven by a high voltage which generates alternating positive and negative pulses [24]. ELDs do not require a backlight and are therefore energy efficient.

2.6 Power supply

In section 1.7 of this paper, it is mentioned that the core body temperature device must be portable and relatively small. This indicates that the device will have an onboard power supply unit in the form of a small battery. First, the difference between a battery and a cell is discussed. The basic difference between a battery and a cell is that a cell is an energy source that delivers DC voltage and current in small quantities, where the functionality of a battery is the same but is arranged in a series or parallel fashion so that voltage levels could be raised [25]. This section shortly describes commonly found batteries in small applications.

2.6.1 Non-rechargeable Batteries

These types of batteries can only be used once, and cannot be recharged. The commonly non-rechargeable batteries used in smaller applications are:

- Alkaline batteries:
  The chemical composition of this type of battery is Zinc (Zn) and Manganese dioxide (MNO_2) with an electrolyte of potassium hydroxide [25]. This battery is in a small cylindrical form and the cost is relatively high.

- Button / Coin cell batteries:
  Lithium and silver oxide chemicals are used as a chemical composition for a coin or button cell battery, although these are also alkaline in nature [25], [26]. Coin cell batteries have a thin, small circular shape and are lightweight with a high nominal voltage ($\pm$3V), but the drawback is that they need a holder.

2.6.2 Rechargeable Batteries

Rechargeable batteries can be recharged and reused. Some commonly used rechargeable batteries in small applications is:

- Li-ion batteries:
  These batteries are made of Lithium metal and are used in portable applications which need high power [25]. Li-ion batteries are very lightweight with a high cell voltage, but a battery protection circuit is needed in the desired application since the battery might explode when the terminals are short-circuited.

- Li-Po batteries:
  Li-Po batteries use polymer gel or polymers electrolyte instead of liquid electrolyte and are mostly the same as the Li-ion technology [25]. Compared to Li-ion batteries, these batteries are highly protected and may be more expensive.

- Ni-Cd batteries:
  The chemical composition of these batteries is Nickel and Cadmium with a low discharge rate [25]. To avoid the growth of crystals on the battery plate, these batteries must be charged more frequently.

2.7 Concluding Remarks

This section reviewed the most commonly used temperature transducers, display technologies, and battery types used in a smaller type of applications. Several methods were discussed to estimate core body temperature from skin surface temperature more accurately without the measurements getting affected by external factors such as ambient temperatures and wind.

Chapter 3 Conceptual Design

In this chapter, a conceptual design of the Body Temperature Measuring Wristband will be presented. The Model-Based Systems Engineering, or MBSE, process will be followed during the design. The MBSE model should not be confused with a mathematical- or simulation model but instead as a conceptual model. The system as a whole will be viewed on a high level, where-after it will be broken down into more detailed levels. A Functional Analysis of the system will be used to determine how the system will monitor and display body temperature, after which an Architectural Synthesis will determine with what functional elements this could be accomplished. After completion of the Functional Analysis, and the Architectural Synthesis, Resource Allocation matrices will be used to test if the design is valid. This chapter will only show the design on a concept level, the detailed design will follow in subsequent chapters.

3.1 Functional Analysis

Functional analysis are a tool to describe the behaviour of the system on a lower level. Functional analysis does not determine or state how a specific function is accomplished, just that it needs to be accomplished. Therefore, the purpose of functional analysis is to identify and clearly state how the system is to work when fully completed. The functional flow block diagrams used in functional analysis uses a level type hierarchy where the system functions are expanded from a high level (level 0) to a lower level, consisting of more detail.

3.1.1 Level 0

The functional analysis are started at the system life cycle, which is also level 0 of the functional flow diagram. Level 0 of the functional flow diagram shows the very high level functions of the system at any point in time. The level 0 functional flow diagram of the system is shown in Figure 3.1.

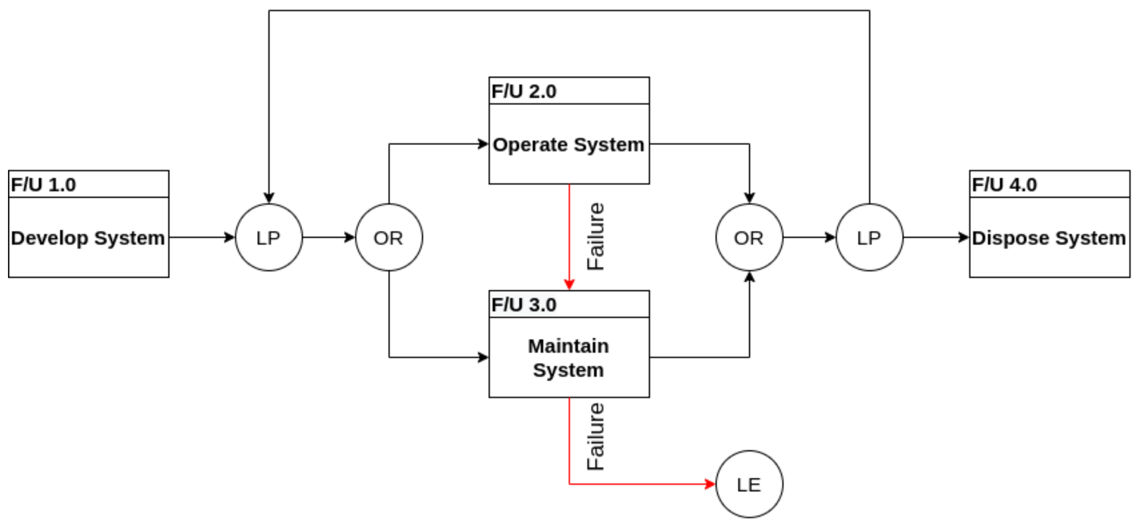

Figure 3.1: Level 0 Functional Flow

The system will mostly be in the Operate System function seen in Figure 3.1. Once a failure occurs in this state, the system will transition to the Maintain System function. If an unrepairable error occurs, the system will exit the loop and the system will be disposed of.

3.1.2 Level 1

The level 1 functional flow diagram provides further detail on how the system functions. The blocks from level 0 are expanded to provide more context on that function of the system. The level 1 functional flow of the system is shown in Figure 3.2.

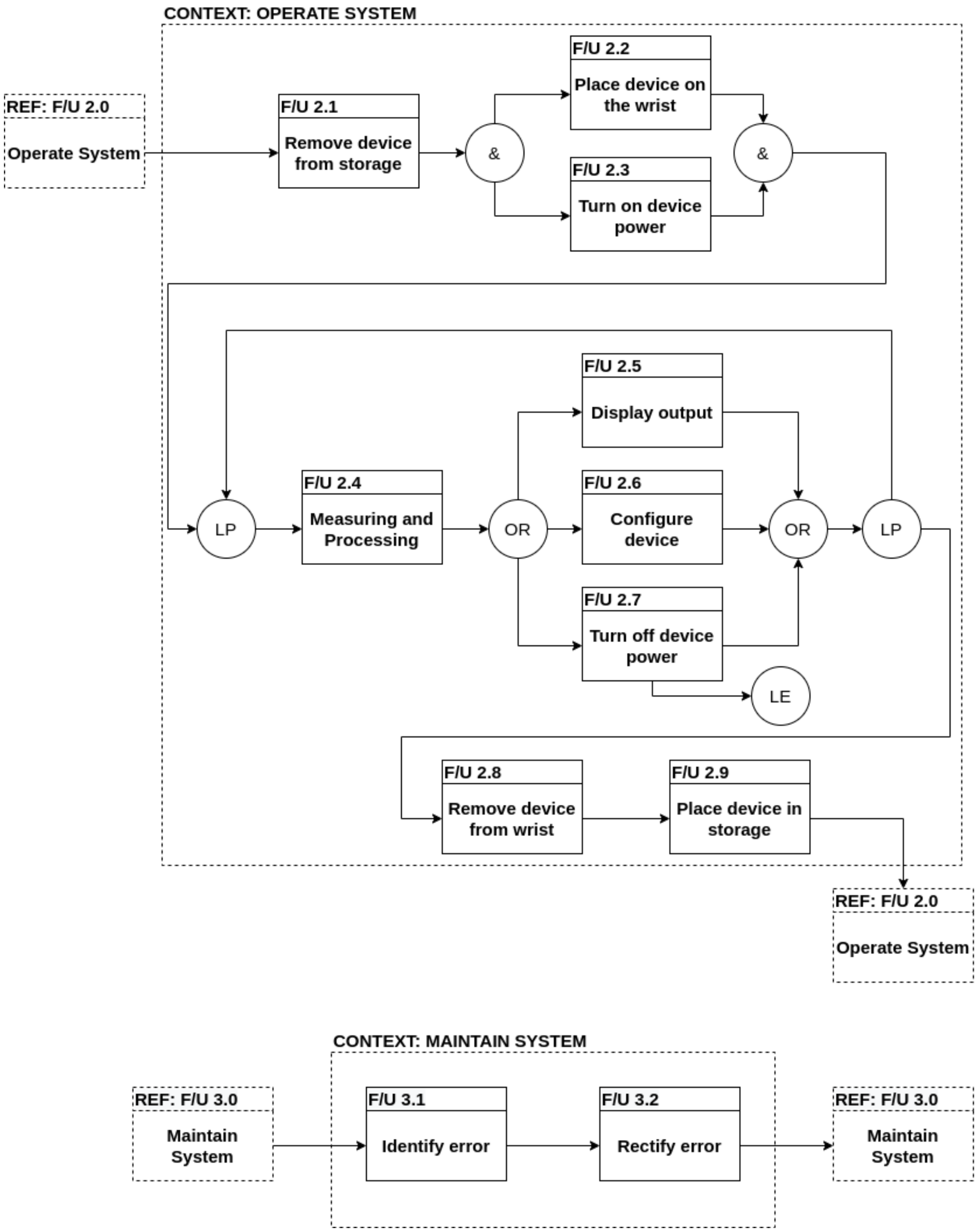

Figure 3.2: Level 1 Functional Flow

The Operate- and Maintain System functions are expanded in level 1 of the functional flow diagram, and more detailed functions within each are revealed. Some of the blocks in level 1 of the functional flow diagram can be expanded even more.

3.1.3 Level 2

Level 2 of the functional flow diagram is the in-depth investigation of the blocks from level 1 that can be expanded further. More information on how the system is to function can be seen in level 2 of the functional flow diagram. Blocks from the Operate System context found in Figure 3.2, that can be expanded further are shown in Figure 3.3 and Figure 3.4.

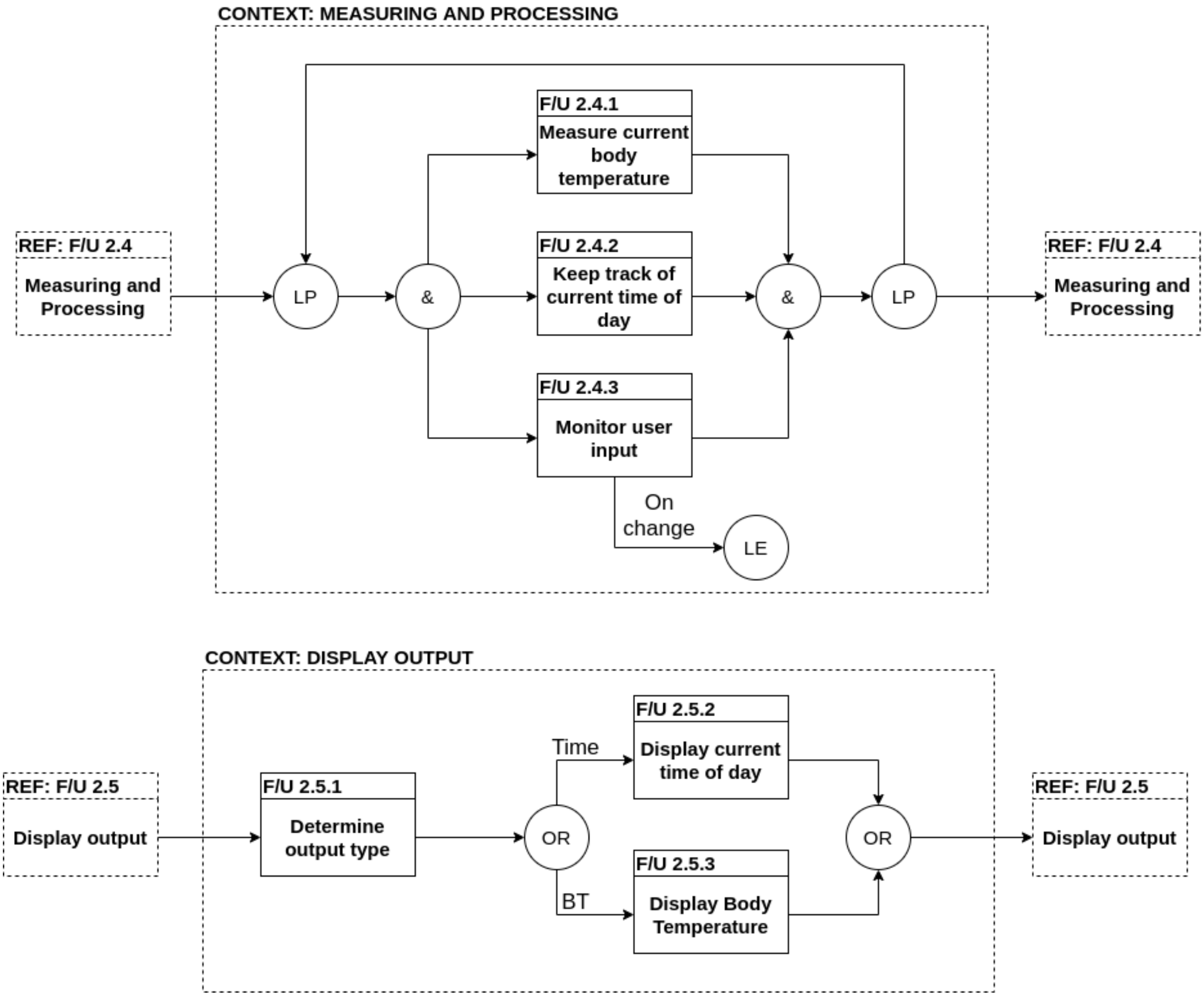

Figure 3.3: Level 2 Functional Flow - Operate System Part 1

From Figure 3.2 and Figure 3.3, it is clear that the system will mostly be in the Measuring and Processing state where the current body temperature of the user will be measured and general timekeeping will be performed. The system will only go to the next function, which is to display certain information to the user, if prompted. After the system has displayed the requested information, it will return to the Measuring and Processing state. Note, however, that general timekeeping will always be performed by the system, no matter the current function. If the user requests to see the current time of day or current body temperature, the applicable output will be shown.

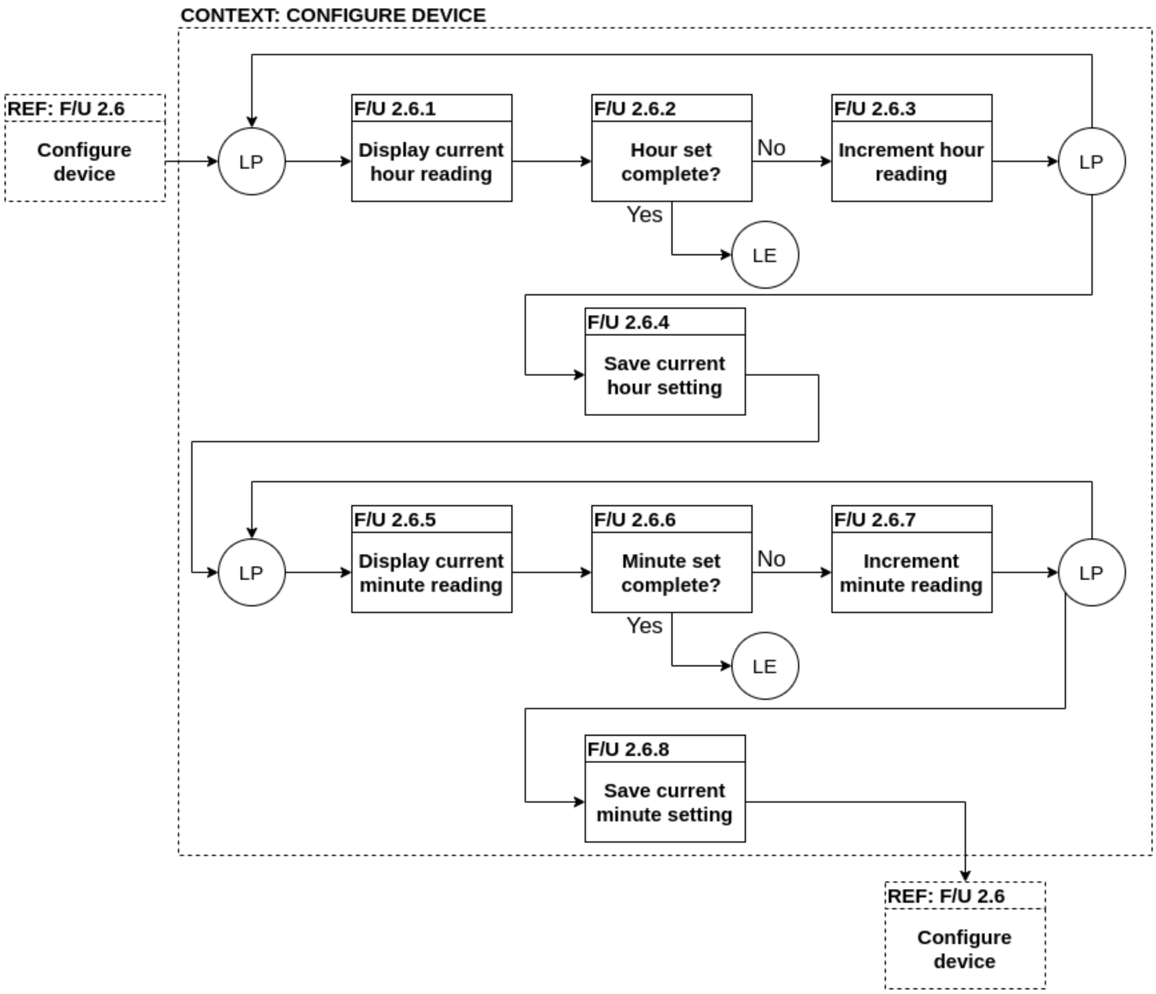

Figure 3.4: Level 2 Functional Flow - Operate System Part 2

Once the user requests to configure the device, the current time of day can be set correctly. The process can be seen in Figure 3.4, where the current saved hour reading is shown to the user, this hour reading will be incremented until the user finds it suitable. The hour reading will then be saved. The same process holds for setting the minute reading.

Blocks from the Maintain System context found in Figure 3.2, that can be expanded further are shown in Figure 3.5.

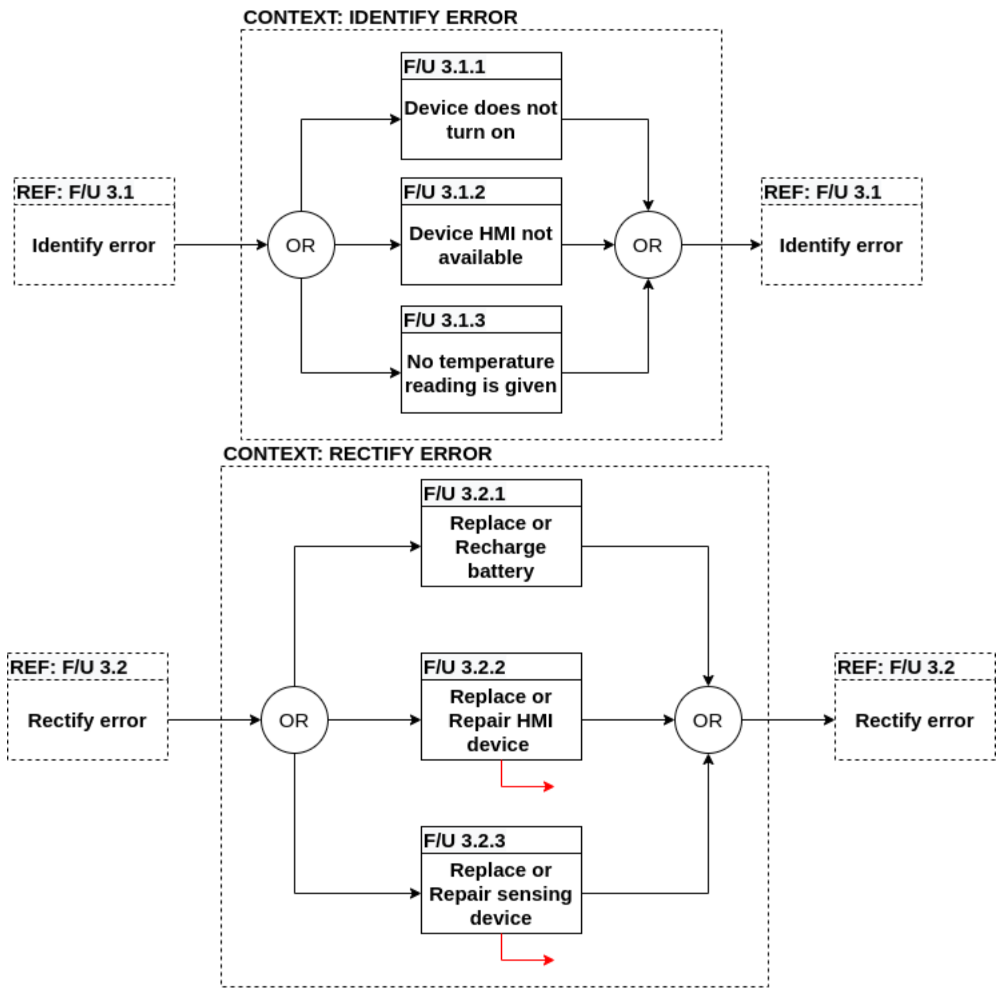

Figure 3.5: Level 2 Functional Flow - Maintain System

The Identify error and Rectify error functions from the Maintain System functional diagram are used to find the origin of the error, as well as to rectify the error. If the error is not repairable, the system will transition to the Dispose System state, as mentioned earlier.

3.2 Architectural Synthesis

Architectural Synthesis is also known as Physical Design and is a process by which the design, that has been captured up to this point in the Functional Analysis, is transformed into something that can be constructed on a concept level. Architectural Synthesis is used to determine what functional elements, or resources, are needed by the system to be able to accomplish the functions mentioned in the previous section. Architectural Synthesis, once again, follows the same level type hierarchy as with the Functional Analysis. In this process, the functional flow elements will be mapped to the physical architecture of the system.

3.2.1 Level 0

The high level physical architecture of the system is shown in Figure 3.6. At this level, the different objects the system will interact with, denoted as functional units, are seen.

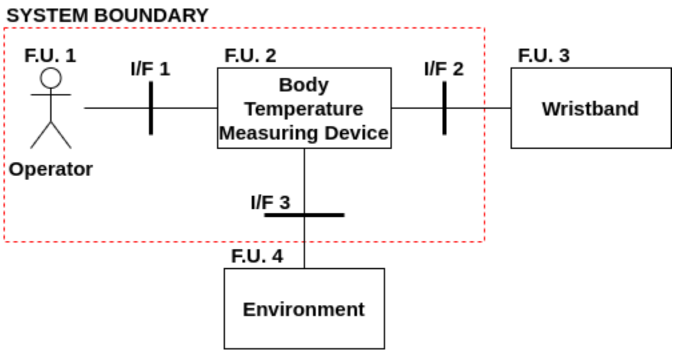

Figure 3.6: Level 0 Physical Architecture

The system boundary clearly shows the system that will be designed, and the operator or user that will be using the system. Functional Unit 2, which is the Body Temperature Measuring Device is the system of interest, and the Physical Architecture of this unit will be expanded in the level to follow, to show the resources needed to design and construct the system.

3.2.2 Level 1

The expansion of the Body Temperature Measuring Device from level 0 are shown in Figure 3.7.

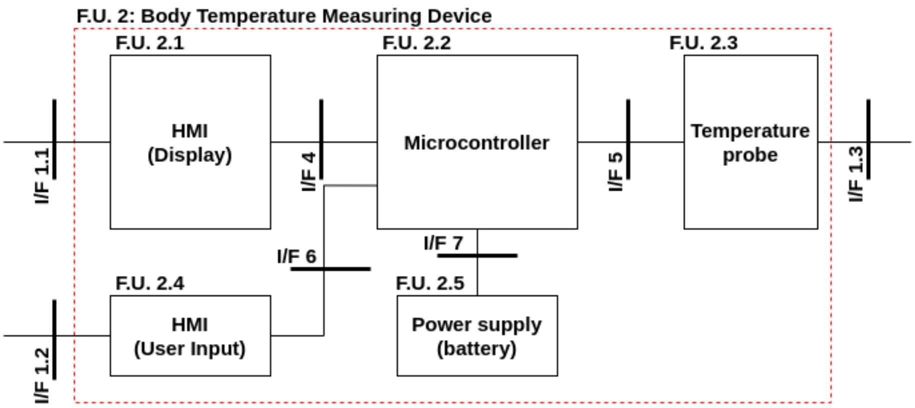

Figure 3.7: Level 1 Physical Architecture

From Figure 3.7 the physical resources needed to implement the system can be seen, as well as how these resources interface with each other and the outside world. This is the Physical Architecture that will be used in the detailed design of the system, where specific components will be assigned to each resource.

3.3 Resource Allocation

Resource Allocation matrices are used to test if the conceptual design is valid. A resource allocation matrix compares the available resources to the functions that needs to be performed. Therefore, the functions from the Functional Analysis are compared to the resources from the Architectural Analysis, to see if there is a resource available to perform the specific function, and vice versa.

The resource allocation matrix that compares the high level functions to the high level resources are shown in Figure 3.8.

	Resources			
Function	F.U. 1 - Operator	F.U. 2 – Body Temperature Measuring Device	F.U. 3 – Wristband	F.U. 4 - Environment
F/U 1,0 – Develop System		X		
F/U 2,0 – Operate System	X	X		X
F/U 3,0 – Maintain System	X	X		
F/U 4,0 – Dispose System	X			

Figure 3.8: High level Resource Allocation matix

The resource allocation matrix that compares the lower level functions to the lower level resources are shown in Figure 3.9.

	Resources				
Function	F.U. 2.1 – HMI (Display)	F.U. 2.2 – Microcontroller	F.U. 2.3 – Temperature probe	F.U. 2.4 – HMI (User Input)	F.U. 2.5 – Power supply
F/U 2.3 – Turn on device power				X	X
F/U 2.4.1 – Measure current body temperature		X	X		
F/U 2.4.2 – Keep track of current time of day		X			
F/U 2.4.3 – Monitor user input		X		X	
F/U 2.5.1 – Determine output type		X		X	
F/U 2.5.2 – Display current time of day	X	X			
F/U 2.5.3 – Display Body Temperature	X	X			
F/U 2.6.1 – Display current hour reading	X	X			
F/U 2.6.2 – Hour set complete?		X		X	
F/U 2.6.3 – Increment hour reading	X	X			
F/U 2.6.4 – Save current hour setting		X			
F/U 2.6.5 – Display current minute reading	X	X			

	Resources				
Function	F.U. 2.1 – HMI (Display)	F.U. 2.2 – Microcontroller	F.U. 2.3 – Temperature probe	F.U. 2.4 – HMI (User Input)	F.U. 2.5 – Power supply
F/U 2.6.6 – Minute set complete?		X		X	
F/U 2.6.7 – Increment minute reading	X	X			
F/U 2.6.8 – Save current minute setting		X			
F/U 2.7 – Turn off device power				X	X
F/U 3.1.1 – Device does not turn on					X
F/U 3.1.2 – Device HMI not available	X			X	
F/U 3.1.3 – No temperature reading is given		X	X		
F/U 3.2.1 – Replace or Repair battery					X
F/U 3.2.2 – Replace or Repair HMI device	X			X	
F/U 3.2.3 – Replace or Repair sensing device			X		

Figure 3.9: Lower level Resource Allocation matix

From the resource allocation matrices it is clear that the concept design is feasible and valid since there are no functions that are not allocated to a resource, and no resources not being used by any functions.

3.4 Concluding Remarks

This section showed the process followed in the concept design of the Medical Wristband Body Temperature Monitor. A Functional Analysis was used to clearly state how the system is to work when fully deployed. After this, an Architectural Synthesis was used to determine the physical architecture of the system, and what resources are available to perform the functions from the Functional Analysis. Finally, Resource Allocation matrices were used for the validation of the concept design.

Chapter 4 Detail Design

In this chapter, the detailed design of the Body Temperature Measuring Wristband will be presented. The detailed design is started with trade-off studies, where Multi-Criteria Decision Matrices (MCDM), together with user-defined utility functions are used to select the specific components required to physically construct the device. After the selection of components, the complete circuit of the Body Temperature Measuring Wristband will be given.

4.1 Trade-off Studies

In this section, trade-off studies will be performed to select specific components to construct the device. The components that will be selected by the trade-off studies include the temperature probe, the microcontroller, the battery, and the display. Each component will have its own set of criteria, as well as utility functions.

4.1.1 Microcontroller

The microcontroller serves as the central processing unit of the body temperature measuring wristband. The microcontroller will be used for communication between the different components, for all the required processing in the process of measuring body temperature, and to distribute power to the components. There are a wide variety of microcontrollers available on the market today, each having its own set of available peripherals, processing speeds, unique features, etc. Therefore, familiar microcontrollers that were available at the time the trade-off studies were conducted, are considered. For the microcontroller of the device, four possibilities were considered:

- PIC24FJ64GA004:
  The PIC24FJ64GA004 family of microcontrollers are developed by Microchip and is 28/44-pin general-purpose, 16-bit flash microcontrollers.

- PIC24FJ256GA705:
  The PIC24FJ256GA705 family of microcontrollers is also developed by Microchip. These are 16-bit general-purpose microcontrollers that have low-power features.

- STM8L15:
  The STM8L15 series are developed by STMicroelectronics and are 8-bit ultra-low-power microcontrollers.

- STM32L071KBT6:
  The STM32L07 series are also developed by STMicroelectronics and are 32-bit ultra-low-power microcontrollers.

The evaluation criteria for selecting the microcontroller is:

- Technical Risk
- Cost per Unit
- Power Consumption
- Clock Speed
- Lead Time

The ability of the designer to correctly implement and interface the specific component with the rest of the circuitry is included in the evaluation criteria as technical risk. Power consumption will play a crucial role in the battery life of the device, and should therefore be kept as low as possible.

Since the current drawn by the microcontroller will depend on the connected components, it is difficult to compare power consumption between different microcontrollers. Therefore, the power consumption of the possible microcontrollers is based on the operating current at the lowest clock speed of that microcontroller. This is done so that the microcontrollers can be compared to one another in terms of power consumption, and clock speed. The cost and lead time of the component should be kept as low as possible. Technical Risk is divided into 5 levels, and is defined as shown in Figure 4.1. Technical Risk will also be included in the evaluation criteria for the rest of the components, and will stay as defined throughout. The utility functions for each criterion are shown in Figure 4.2.

Risk Number	Risk Level	Utility	Risk Description
5	Very High	0.2	Unfamiliar technology, applied in an unfamiliar context
4	High	0.4	New technology, applied in a new context
3	Medium	0.6	Familiar technology, applied in a new context / New technology, applied in a familiar context
2	Low	0.8	Familiar technology, applied in a similar context
1	Very Low	1	Familiar technology, reapplied in familiar context

Figure 4.1: Technical Risk Definition

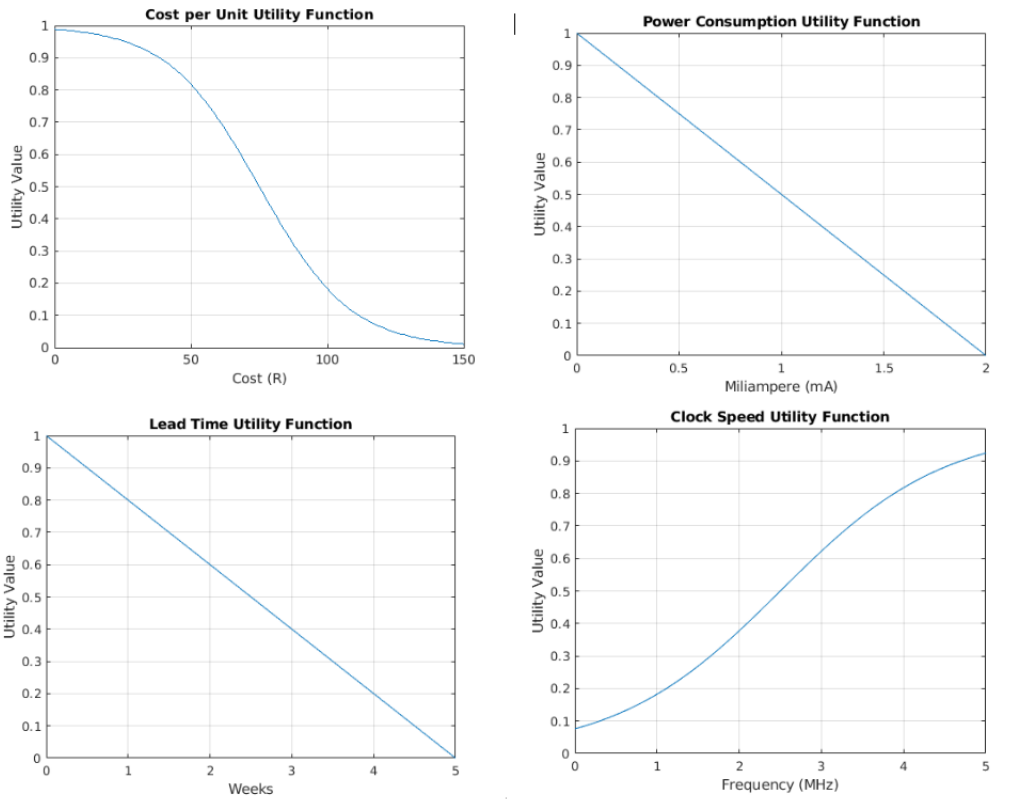

Figure 4.2: Microcontroller - Utility Functions

The Multi-Criteria Decision Matrices (MCDM) for each microcontroller is shown in Figure 4.3. Note that the total weighted score is multiplied together, and then scaled for legibility. The weights of the evaluation criteria are chosen according to the importance of the criterion. Power consumption was favoured above clock speed since clock speeds are not as important as power consumption in this energy-efficient application which does require not as much processing. The rest of the evaluation criteria have the same weight as they are of equal importance. All the technical values are obtained from the respective data sheets, the cost is included without tax or shipping to compare the basic microcontroller cost, and the lead time includes shipping.

PIC24FJ256GA705 Family				
0.15593472	Weight	Score	Utility Value	Weighted Score
Technical Risk	0.2	3	0.6	0.12
Cost per Unit	0.2	R27.33	0.94	0.188
Power Consumption	0.3	365µA	0.8	0.24
Clock Speed	0.1	1MHz	0.18	0.018
Lead Time	0.2	4-6 business days	0.8	0[illegible]
Total	1			0.15593472

STM8L15 Series				
0.032783616	Weight	Score	Utility Value	Weighted Score
Technical Risk	0.2	3	0.6	0.12
Cost per Unit	0.2	R32.07	0.93	0.186
Power Consumption	0.3	635µA	0.68	0.204
Clock Speed	0.1	1MHz	0.18	0.018
Lead Time	0.2	4 weeks	0.2	0.04
Total	1			0.032783616

STM32L071 Series				
0.330624	Weight	Score	Utility Value	Weighted Score
Technical Risk	0.2	3	0.6	0.12
Cost per Unit	0.2	R75.04	0.5	0.1
Power Consumption	0.3	375µA	0.8	0.24
Clock Speed	0.1	4MHz	0.82	0.082
Lead Time	0.2	4-6 busines days + 4-6 business days for delivery	0.7	0.14
Total	1			0.330624

PIC24FJ64GA004 Family				
0.0224352	Weight	Score	Utility Value	Weighted Score
Technical Risk	0.2	3	0.6	0.12
Cost per Unit	0.2	R81.5	0.41	0.082
Power Consumption	0.3	1.6mA	0.2	0.06
Clock Speed	0.1	2MHz	0.38	0.038
Lead Time	0.2	4-6 busines days for back order + 4-6 business days for delivery	0.5	0.1
Total	1			0.0224352

Figure 4.3: Microcontroller - MCDM

From the trade-off study, it is clear that the STM32L071 series of microcontrollers are best suited for this application. More specifically, the STM32L071KBT6 from this series will be used. This microcontroller includes two I2C peripherals, Analog to Digital converters (ADC), Real-Time Clock (RTC) functionality, 128K bytes for program memory, and 20K bytes for RAM. This device has 32 pins, where 25 of them are available for GPIO (General Purpose Input/Output), which will be used for display and input purposes. The STM32L071KBT6 features low power consumption in run mode, and have ultra-low power modes available such as Standby mode (0.29μA), Stop mode (0.43μA) and Stop mode with RTC (0.86μA).

4.1.2 Temperature Probe

The temperature probe will be used to measure the body temperature of the user. For the temperature probe, four possibilities were considered. All of these possibilities have a measurement range that includes the required range for body temperature, and since the chosen microcontroller has many peripherals available, the options may use any possible interface to communicate. The possible temperature probes are:

- LM35:
  The LM35 is an analog temperature sensor that has an output voltage directly proportional to the measured temperature.
- TMP117:
  The TMP117 is a digital temperature sensor integrated circuit (IC) that uses the I2C/SMBus communication protocol.

- DS18B20:
  The DS18B20 is a digital thermometer that utilises 1-Wire technology for communication with a microprocessor.

- MAX30205:
  The MAX30205 is an accurate, low-voltage digital temperature sensor that uses the I2C protocol for communication.

The evaluation criteria for selecting the temperature probe is:

- Technical Risk.
- Measurement Accuracy.
- Cost per Unit.
- Power Consumption.
- Lead Time.

Since body temperature plays a crucial role in one's health, it must be measured accurately. Therefore, the measurement accuracy of the temperature sensor is included in the criteria. The sensor cost and lead time must be kept as low as possible, as well as the power consumption since the device will be battery operated. The utility functions for each criterion are now given and are shown in Figure 4.4.

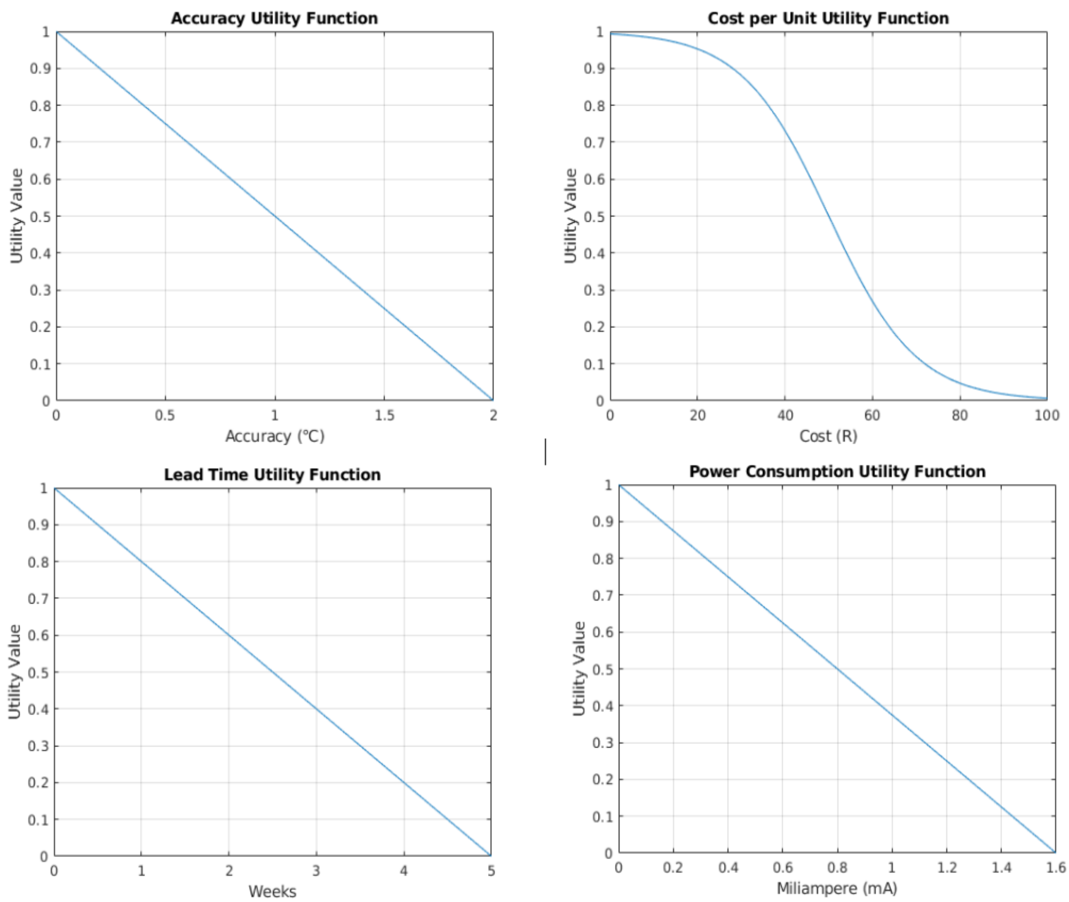

Figure 4.4: Temperature Probe - Utility Functions

The Multi-Criteria Decision Matrices (MCDM) for each possibility is shown in Figure 4.5. Note that the total weighted score is multiplied together, and then once again scaled for legibility. The weights of the evaluation criteria are chosen the same since all the criteria are of equal importance when choosing the temperature probe. All the technical values are obtained from the respective data sheets, the cost is included without tax or shipping to compare the basic sensor cost, and the lead time includes shipping.

LM35				
0.42538496	Weight	Score	Utility Value	Weighted Score
Technical Risk	0.2	2	0.8	0.16
Measurement Accuracy	0.2	±1.5°C	0.25	0.05
Cost per Unit	0.2	R25.18	0.91	0.182
Power Consumption	0.2	138μA	0.913	0.1826
Lead Time	0.2	4-6 business days	0.8	0.16
Total	1			0.42538496

TMP117				
0.16985088	Weight	Score	Utility Value	Weighted Score
Technical Risk	0.2	3	0.6	0.12
Measurement Accuracy	0.2	±0.1°C	0.95	0.19
Cost per Unit	0.2	R61.20	0.24	0.048
Power Consumption	0.2	3.5μA	0.97	0.194
Lead Time	0.2	3 weeks	0.4	0.08
Total	1			0.16985088

DS18B20				
0.0056832	Weight	Score	Utility Value	Weighted Score
Technical Risk	0.2	4	0.4	0.08
Measurement Accuracy	0.2	±0.5°C	0.75	0.15
Cost per Unit	0.2	R90.55	0.02	0.004
Power Consumption	0.2	1mA	0.37	0.074
Lead Time	0.2	4-6 business days	0.8	0.16
Total	1			0.0056832

MAX30205				
0.55186944	Weight	Score	Utility Value	Weighted Score
Technical Risk	0.2	3	0.6	0.12
Measurement Accuracy	0.2	±0.1°C	0.95	0.19
Cost per Unit	0.2	R46.26	0.61	0.122
Power Consumption	0.2	600μA	0.62	0.124
Lead Time	0.2	4-6 business days	0.8	0.16
Total	1			0.55186944

Figure 4.5: Temperature Probe - MCDM

Therefore, the temperature probe that will be used is the MAX30205 digital temperature sensor.

4.1.3 Display

The display will show the user the measured body temperature, as well as the current time of day. The display will also be used by the user to configure the device. There are various types of displays on the market, ranging from touch screens to LED matrix displays, all coming in a wide variety of sizes. The displays that are considered must be compact and small, energy-efficient, and touch screen are not required. In the case where a driver IC is needed by the display, only the displays that come with the required IC built-in were considered since they do not require any external components or configurations to work properly. For the display of the device, four possibilities were considered:

- 0.91 Inch OLED Display Module:
  This is an OLED display with 128x32 pixels that comes with an embedded controller that communicates via the I2C interface.

- 4 Digit 7-Segment LED Display:
  This is a display consisting of four standard 7-segment displays that are connected together in one package.

- Midas 0.49in White Passive Matrix OLED Display:
  This is a 64x32 resolution OLED display that has a white-on-black appearance, that also comes with an embedded controller that communicates via I2C.

- RS PRO TFT LCD Colour Display:
  This display is a full-colour TFT LCD module with a normally white backlight. The screen has a 160x80 resolution and the display communicates via a 3- or 4-wire serial peripheral interface.

The evaluation criteria for selecting the display is:

- Technical Risk.
- Size of the Module.
- Cost per Unit.
- Power Consumption.
- Lead Time.

The size of the display will play a crucial role in the overall size of the final device and should be kept as small, yet as legible as possible since the device will be in the form of a wristband. The device will be battery operated, and the power consumption by the display should be as low as possible in order to provide longer battery life. The cost and lead time should, once again, be as low as possible. The utility functions for each criterion are shown in Figure 4.6.

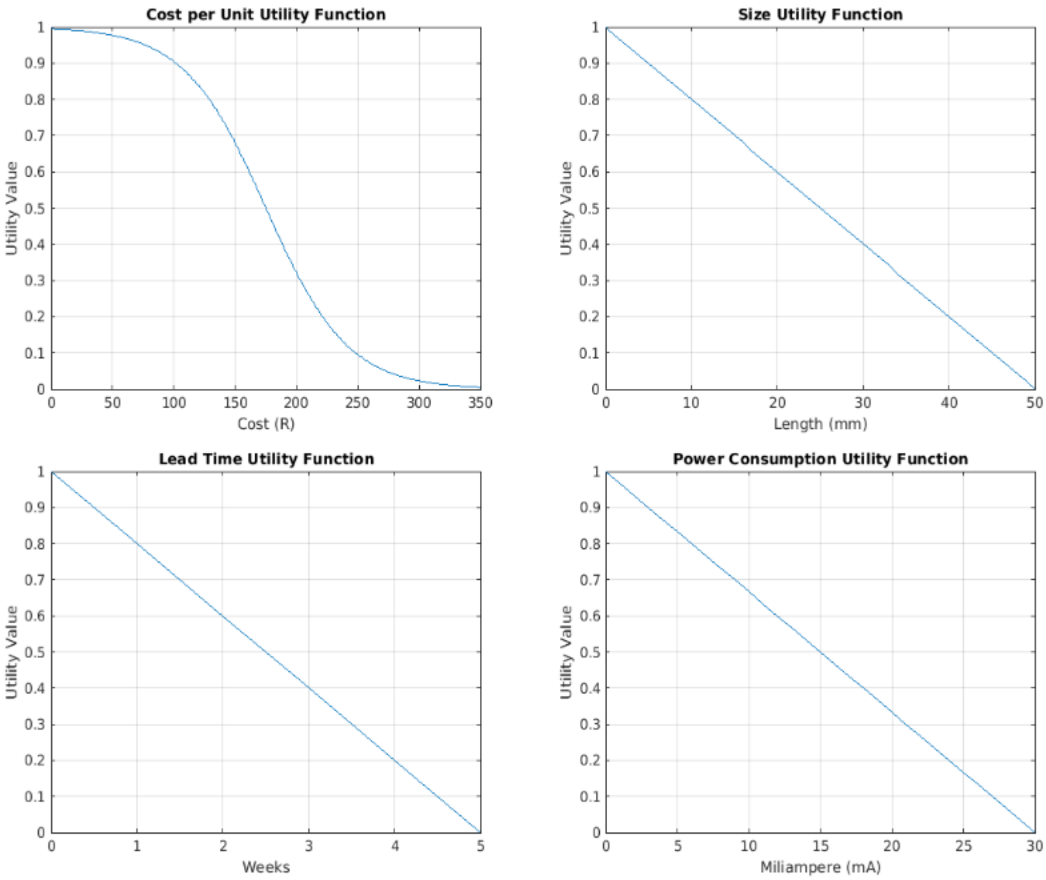

Figure 4.6: Display - Utility Functions

The Multi-Criteria Decision Matrices (MCDM) for each possibility is shown in Figure 4.7. All the technical values are obtained from the respective data sheets, the cost is included without tax or shipping to compare the basic sensor cost, and the lead time includes shipping. Note that the total weighted score is multiplied together, after which it is then scaled for legibility. The weights of the evaluation criteria are chosen the same since all the criteria are equally important. Although the size of the screen plays a very important role, it cannot have a higher weight than the other criteria since they are of equal importance.

0.91 Inch OLED Display Module				
0.115858944	Weight	Score	Utility Value	Weighted Score
Technical Risk	0.2	3	0.6	0.12
Cost per Unit	0.2	R144.61	0.72	0.144
Size	0.2	36 x 12.5 x 3 mm	0.29	0.058
Power Consumption	0.2	20mA*	0.34	0.068
Lead Time	0.2	1 - 3 business days	0.85	0.17
Total	1			0.115858944

4 Digit 7-Segment LED Display				
0.051132192	Weight	Score	Utility Value	Weighted Score
Technical Risk	0.2	3	0.6	0.12
Cost per Unit	0.2	R47.167	0.97	0.194
Size	0.2	40.2 x 12.8 x 7 mm	0.19	0.038
Power Consumption	0.2	25mA	0.17	0.034
Lead Time	0.2	1 - 3 business days	0.85	0.17
Total	1			0.051132192

Midas White Passive Matrix OLED Display				
0.52706304	Weight	Score	Utility Value	Weighted Score
Technical Risk	0.2	3	0.6	0.12
Cost per Unit	0.2	R112.70	0.86	0.172
Size	0.2	14.85 x 16.6 x 2.36 mm	0.7	0.14
Power Consumption	0.2	13mA	0.57	0.114
Lead Time	0.2	4 - 6 business days	0.8	0.16
Total	1			0.52706304

RS PRO TFT LCD Colour Display				
0.00417792	Weight	Score	Utility Value	Weighted Score
Technical Risk	0.2	3	0.6	0.12
Cost per Unit	0.2	R301.14	0.02	0.004
Size	0.2	30 x 28 x 3 mm	0.4	0.08
Power Consumption	0.2	20mA*	0.34	0.068
Lead Time	0.2	4 - 6 business days	0.8	0.16
Total	1			0.00417792

Figure 4.7: Display - MCDM

From the trade-off study, it is clear that the White Passive Matrix OLED Display from Midas will be best suited for the body temperature measuring device. As mentioned previously, this display has a 64x32 resolution and has the SSD1306 controller built-in on the display module, and communicates via the I2C interface.

4.1.4 Battery

The battery will provide power to the microcontroller, as well as the other components of the device. For the battery, two different possibilities that are easily accessible were considered:

- RS PRO LIR2032:
  This is a rechargeable button battery with a chemical composition of Lithium-ion.
- RS PRO Lithium Polymer battery:
  This is a Li-Polymer rechargeable battery that has a low self-discharge and comes pre-wired with bare wire terminals.
- Panasonic CR2032 Button battery:
  This is a non-rechargeable coin cell battery that have a low self-discharge rate.

The evaluation criteria for selecting the battery is:

- Technical Risk
- Cost per Unit
- Size
- Capacity
- Lead Time

Since the developed device will be in the form of a wristband, the size of the product must be small, to provide maximum comfort. In order to compare the button batteries to the battery that has a square shape, only the length of each will be considered. The capacity of the battery will determine how long the body temperature wristband will last, and therefore, the higher the capacity, the better. As previously, the cost and lead time should be as low as possible. The utility functions for each criterion for the battery are shown in Figure 4.8, and the Technical Risks are defined once again as in Figure 4.1.

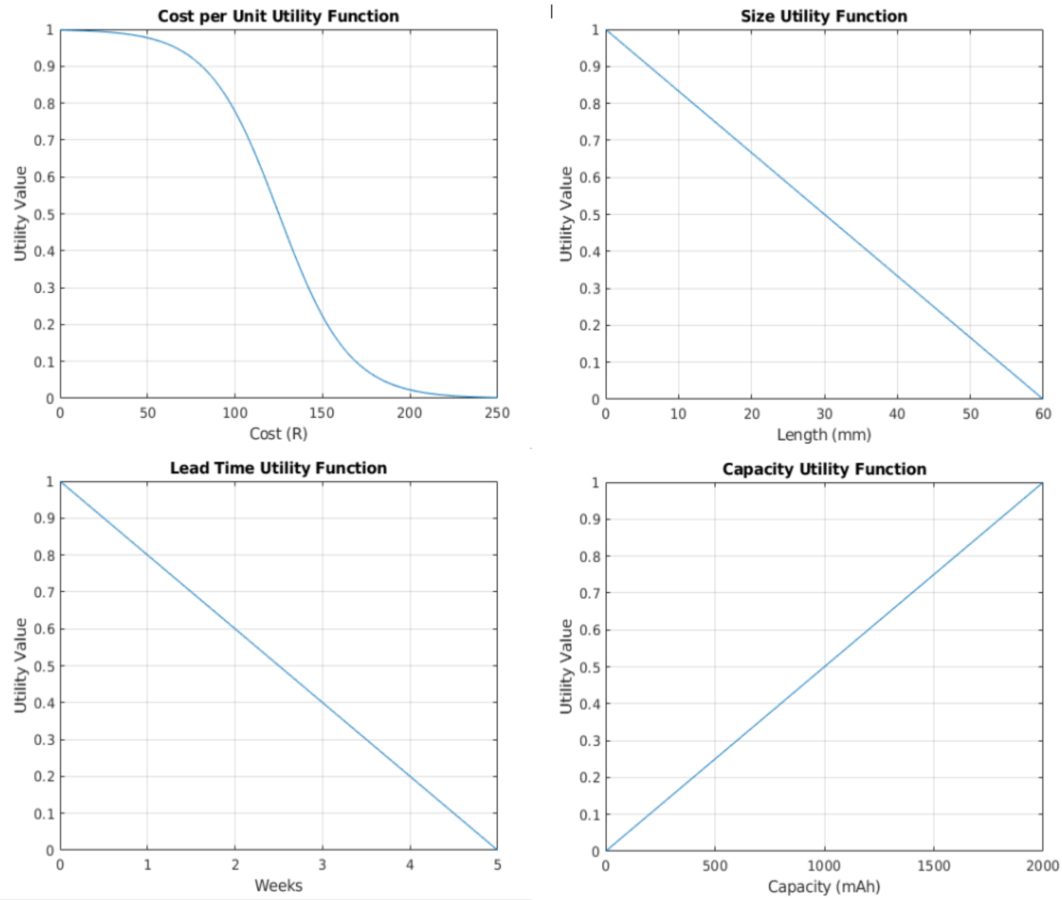

Figure 4.8: Battery - Utility Functions

The Multi-Criteria Decision Matrices (MCDM) for each battery is shown in Figure 4.9. Note that the total weighted score is multiplied together, and then scaled for legibility. Capacity and size are favoured in terms of the evaluation weight above the other criteria since they are of most importance in choosing the battery. Technical Risk is given a lower weight as the use of batteries is straightforward, although battery management and recharging may be more complex. Lead time is also given a lower weight since batteries are relatively easily accessible. The cost is included without tax or shipping to compare the basic battery cost, the lead time includes shipping, and all the technical values are obtained from the respective datasheets.

RS PRO LIR2032 Button Battery				
0.1079568	Weight	Score	Utility Value	Weighted Score
Technical Risk	0.1	3	0.6	0.06
Cost per Unit	0.2	R31.5	0.98	0.196
Size	0.3	20 mm diameter x 3.2 mm height	0.6	0.18
Capacity	0.3	40mAh	0.02	0.006
Lead Time	0.1	1 - 3 business days	0.85	0.085
Total	1			0.1079568

RS PRO Lithium Polymer Rechargeable Battery				
0.0103275	Weight	Score	Utility Value	Weighted Score
Technical Risk	0.1	3	0.6	0.06
Cost per Unit	0.2	R228	0.01	0.002
Size	0.3	53.5 x 35 x 10.4 mm	0.15	0.045
Capacity	0.3	1.5Ah	0.75	0.225
Lead Time	0.1	1 - 3 business days	0.85	0.085
Total	1			0.0103275

Panasonic CR2032 Button Battery				
0.6873984	Weight	Score	Utility Value	Weighted Score
Technical Risk	0.1	3	0.6	0.06
Cost per Unit	0.2	34.44	0.96	0.192
Size	0.3	20 mm diameter x 3.2 mm height	0.6	0.18
Capacity	0.3	220mAh	0.13	0.039
Lead Time	0.1	1 - 3 business days	0.85	0.085
Total	1			0.6873984

Figure 4.9: Battery - MCDM

Therefore, the battery that will be used is the Panasonic CR2032 Button battery. This battery is non-rechargeable as mentioned previously, and it has a nominal voltage of 3.0V. The nominal voltage of the battery will be sufficient to power the microcontroller, which has a supply voltage range of 1.65V to 3.6V. This nominal voltage is also sufficient to power the temperature probe which has a 2.7V to 3.3V supply voltage rating, and the display, which can be powered from 2V to 5V. The big advantage of this battery is that no extra recharging circuitry, which will consume a lot of space, are needed. This type of battery is also commonly available in grocery stores, garages, etc. making it easily accessible when it must be replaced.

4.1.5 Measurement Technique

4.2 Physical Architecture

In this section the updated physical architecture of the Medical Wristband Body Temperature Monitor is shown. The components from the trade-off studies in the previous section are added to the diagram, as well as some interfaces between the components. The detailed physical architecture of the device is shown in Figure 4.10.

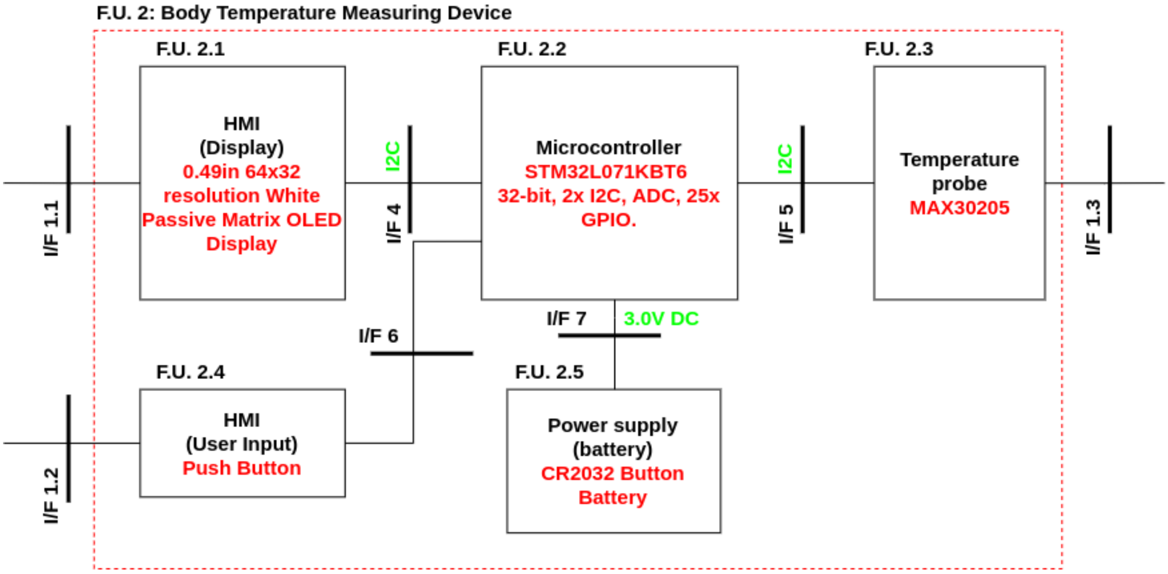

Figure 4.10: Detailed Physical Architecture

4.3 Schematics

This section will show the schematics for the Body Temperature Measuring device. The full schematic of the device will be broken down into sub-systems to aid legibility. The sub-systems for the Body Temperature Measuring device are as follow:

- The Microcontroller and all relevant components.
- The Temperature sensor and all relevant components.
- The user input buttons.
- The Power supply unit.
- External component connectors.

4.3.1 Microcontroller

This section will show the schematic for the microcontroller of the device. All the components related to the microcontroller, such as decoupling capacitors, resistors, etc. will also be shown in the schematic. The microcontroller and relevant circuits can be referred to as the processing unit of the device. The schematic for the processing unit of the device is shown in Figure 4.11.

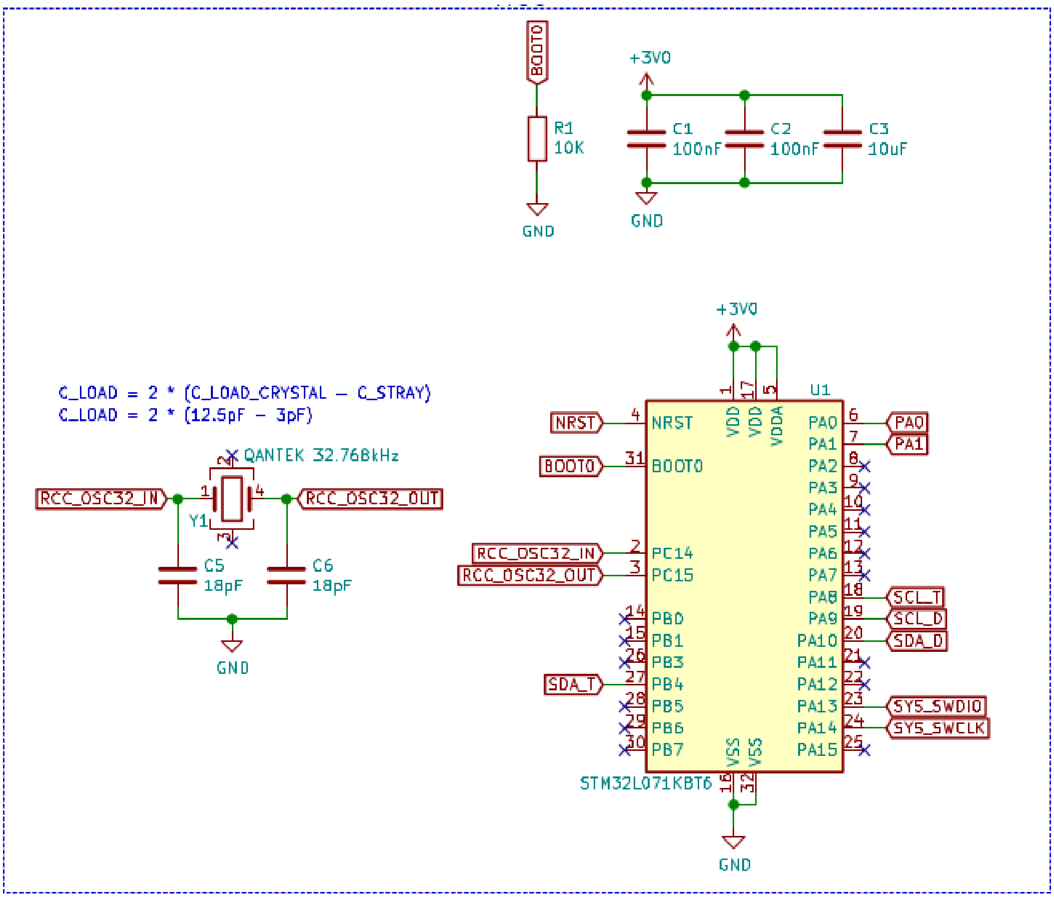

Figure 4.11: Schematic: Microcontroller

From Figure 4.11 all the connections to and from the microcontroller can be seen as the connections are labelled. These labels show the physical connections to all the other components of the device, as two labels with the same value are connected.

Figure 4.11 shows that there are three decoupling capacitors for the microcontroller. From the datasheet of the STM32L071KBT6, ST recommends that for every V_{DD} and V_{SS} pair of the microcontroller, a $100nF$ capacitor is needed. They also recommend that in addition to the $N \times 100nF$ capacitors, one $10\mu F$ capacitor is needed. It can be seen that the $BOOT0$ pin of the microcontroller is pulled to ground via a resistor. This is done to hold the logic level near 0V on this pin. The $BOOT0$ pin must be at the defined low logic level (ground) to select the main flash memory as the boot space of the microcontroller.

A low-speed external (LSE) crystal oscillator is also connected to the microcontroller. This crystal oscillator will be used as the frequency source of the RTC. The microcontroller features a low-speed internal RC oscillator that may be used for this purpose, but internal low-speed clocks tend to have a low accuracy, which is not ideal for time-keeping purposes. The decision is therefore made to add a $32.768kHz$ external crystal oscillator to the microcontroller. This value of $32.768kHz$ is commonly used as the frequency in RTC applications since it is a power of 2 (2^{15}) value and one can get a precise 1 second period ($1Hz$) by using a 15 stage binary counter. Sometimes, a feed resistor is needed between the oscillator and the microcontroller. A feed resistor limits the amount of drive going to and from the crystal ensuring that the crystal waveform is not distorted. However, ST strongly recommends not to add an external resistor between the oscillator pins of the microcontroller. Two load capacitors can be seen at the crystal oscillator. The values of the load capacitors are calculated by using the following formula:

$$C_{load} = 2 \times (C_{crystal} - C_{stray}) \tag{4.1}$$

Where $C_{crystal}$ is the load capacitance of the crystal which is found in the datasheet as $12.5pF$, and C_{stray} is the stray capacitance of the PCB which is assumed as $3pF$. Therefore, $19pF$ is the calculated value of the load capacitors, and the nearest commercial capacitor value that could be found is $18pF$.

4.3.2 Temperature Sensor

This section will show the schematic for the temperature sensor of the device. The schematic for the MAX30205 temperature sensor is shown in Figure 4.12.

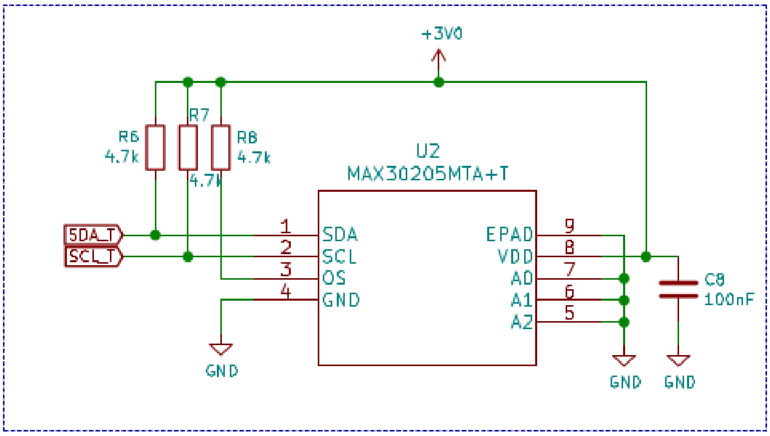

Figure 4.12: Schematic: Temperature sensor

From Figure 4.12 it can be seen that three pull-up resistors are needed, one for the Serial Clock Line (SCL), one for Serial Data Line (SDA), and one for Over-temperature Shut-down (OS). It can also be seen that a $100nF$ capacitor is needed between V_{DD} and ground. This is obtained from an application circuit in the MAX30205 datasheet. This temperature sensor communicates via I2C and in Figure 4.12 it shows that the MAX30205 are connected to pins 18 (SCL) and 27 (SDA) of the microcontroller. Since $A0$, $A1$, and $A2$ are all connected to ground, the slave address in hex of the temperature sensor is 90h.

4.3.3 User Input buttons

The user input buttons will be used to wake the device from standby mode, as well as to change what is being displayed by the device. The device will also be configured by one of the input buttons. The schematics for the two input buttons are shown in Figure 4.13.

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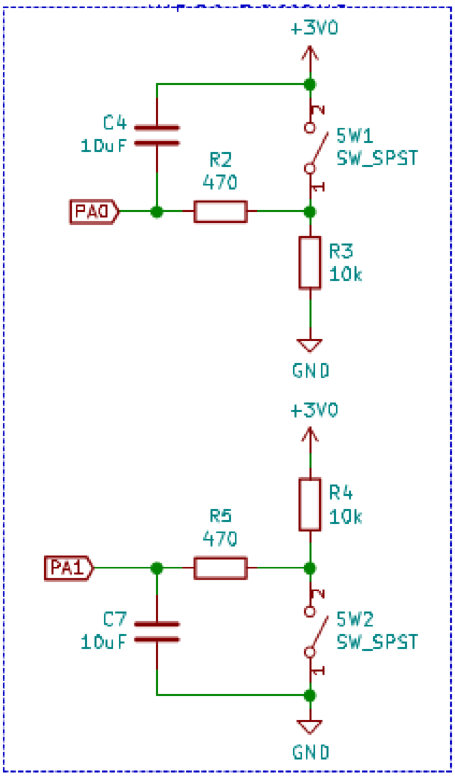

Figure 4.13: Schematic: Input Buttons

From Figure 4.13 it can be seen that one of the input buttons of the device has an active-high configuration, whilst the other input button has an active-low configuration. The active-high button is used to wake the microcontroller from standby or low-power mode. This needs to be an active-high configuration since the device will only wake on the rising edge of any of the three wake-up (WKUP) pins. Pin 6 (PA0) is used in this case to wake the device. The active-low button is used as an input button so that the user can change what is being displayed by the device, and also set the current time and date, etc. The reason an active-low configuration is used to capture the input of the user is to ensure that it is functional if and only if an intentional logic state is applied. Therefore, ambiguous floating input conditions are avoided in the process. The input button is connected to pin 7 (PA1) of the microcontroller.

It can also be seen that both the buttons have a de-bouncing circuit. This is to deal with the mechanical bounce of the switch contacts after they are hit together (button was pressed) since most microcontrollers will interpret this bouncing action as separate hits of the button.

4.3.4 Power Supply

This section will show the power supply of the body temperature measuring device. The device will be battery operated as mentioned previously. The power supply of the device is shown in Figure 4.14.

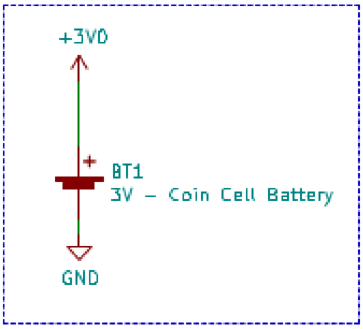

Figure 4.14: Schematic: Power Supply

From Figure 4.14 it can be seen that the power supply of the device is just a single coin cell battery. No voltage regulator is required since all of the components of the device have an input voltage range that includes the 3V being delivered by the battery.

4.3.5 External Component Connectors

The display, as well as the flash programmer must connect to the device externally. This section will show the schematics for the external component connectors.

Display Connector

Although the display is part of the body temperature measuring device, it will be connected externally to the device since the display is in the form of a module. The connection between the display and the main circuit of the body temperature device will be made through header pins. Therefore, to ensure communication between the microcontroller and the display, it must be accommodated for in the schematic. The display that will be used (determined in subsection 4.1.3) have the following pinout as obtained from the datasheet:

Table 4.1: *Display pinout*

Pin	Symbol
1	GND
2	VCC
3	SCL
4	SDA

The schematic for the display connector is shown in Figure 4.15. The display communicates to the microcontroller via the I2C interface, and it will be connected to pins 19 (SCL) and 20 (SDA) of the microcontroller via the display connector..

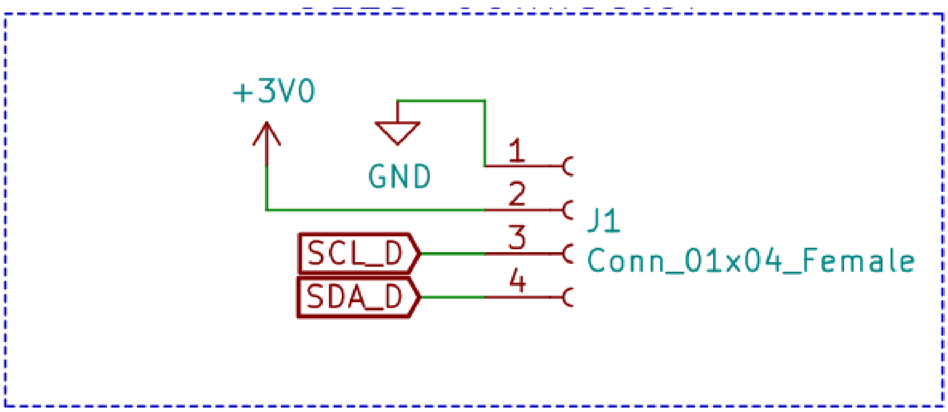

Figure 4.15: Schematic: Display Connector

Flash Connector

The Flash connector or from now on SWD (Serial Wire Debug) connector, will be used to flash program code onto the microcontroller. An ST-LINK/V2-1 will be used to flash the code onto the device. The ST-LINK that will be used have the following pinout, which shows the required connections to the microcontroller in order to flash program code on to the device:

Table 4.2: *SWD Connector*

Pin	Symbol	Designation
1	VDD_Target	VDD from application
2	SWCLK	SWD clock
3	GND	Ground
4	SWDIO	SWD data input/output
5	NRST	RESET of target STM32

The schematic for the SWD connector is shown in Figure 4.16. The connector allows communication between the microcontroller and the ST-LINK, and is connected to pins 4 (NRST), 23 (SYS_SWDIO) and 24 (SYS_SWCLK) of the microcontroller.

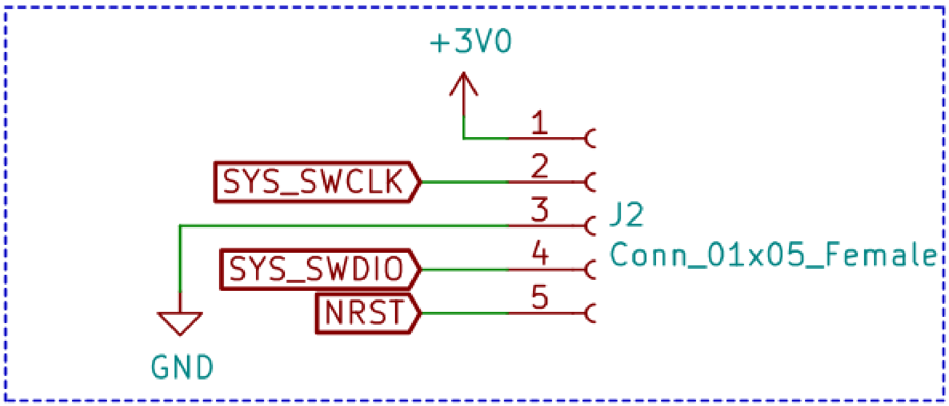

Figure 4.16: Schematic: SWD Connector

4.4 Firmware

Embedded Software flow charts /

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