Exploration into Thermal Regulation Systems for Yellow-Billed Hornbill

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Abbreviations

MCU microcontroller unit

MPPT maximum power point tracking

PSU power supply unit

PWM Pulse width modulation

TEC Thermoelectric Cooler

UV Ultraviolet

Chapter 1

Introduction

> Philosophers have hitherto only interpreted the world in various ways; the point is to change it.
>
> —*Karl Marx*

1.1 Background

Global warming is an ongoing force that continues to reshape the environment and yet most of its consequences are still to be seen. The Kalahari, an already harsh climate, is already facing the effects; increased air temperate, intensified and frequent heatwaves and more frequent droughts [3]. Fig 1.1 clearly shows a drastic increase in the number of extremely hot days past 2020 [1].

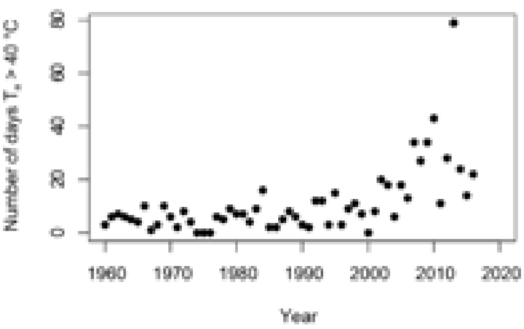


Figure 1.1: Number of days where T>40° C in the Kalahari [1]

These factors have already had major consequences on wildlife, particularly in birds that are already close to the upper limit of their thermal tolerance [1] This makes studying the Kalahari significant as it is indicative of the effects harsher environments that global warming could bring.

Ornithologist Ben Murphy is researching the Southern Yellow-Billed Hornbill and how the changing climate is impacting them. Their breeding strategy involves the female bird sealing herself into the nest cavity, laying eggs, and remaining with the chicks for an extended period (around 53 days) [4]. During this time the female and chicks rely solely on the male to bring food to the nest [3]. Due to increased temperatures attributed to global warming, nest temperatures have exceeded nest conditions often exceed the bird's thermal tolerance. This harsh reality forces the female to resort to cannibalizing some eggs or chicks to regain energy [1]

Without a system to regulate thermal conditions, breeding success is declining, chick development is hampered, and the species faces potential extinction.

1.2 Objectives

The primary objectives of this project were to develop a robust thermal management and monitoring system for a nest box, utilizing solar power and rechargeable batteries to sustainably power the system. The project aims to assist an ornithologist in cooling the nest to a maximum of 35°C, maximizing the passive cooling capability and preventing active cooling from disturbing the birds. The project is broken into the design and integration of essential modules including power regulation, cooling, mechanical reinforcement, and sensing to ensure optimal environmental conditions within the nest box. Establish a user-friendly interface for remote monitoring and data retrieval, allowing stakeholders to access real-time temperature data and system performance logs via a mobile-compatible web server hosted wirelessly.

1.3 Scope & Limitations

The objectives will be achieved by segmenting the task into three subsystems, each assigned to a group member for solution identification. Subsequently, all subsystems will be integrated to form a comprehensive solution. Limitations include a budget constraint of R2000.00 for the entire project, suppliers confined to the local geographical area and 12 weeks as the time for the completion of the project including the time required for ordering and receiving components from local suppliers.

1.4 Report Outline

The report introduces the background, objectives, limitations and scope in the introduction chapter 1. The relevant literature is reviewed in chapter 3 and subsequently, the proposed solutions are defined in chapter 2. Chapter 4 details the design and testing of the power subsystem, followed by chapter 5 which goes into detail on the selection of the cooling system and box design. Chapters 6 & 7 discuss the selection, design and implementation of the sensor and front end of the cooling system. Lastly, the chapter 8 provides the findings and future recommendations for the project.

Chapter 2

Problem Statement

We are trying to assist Ben, a PhD student who is working in the Kalahari, in his conservation attempts of the Southern Yellow-billed Hornbill by monitoring and regulating the temperature within the nests during the breeding season.

2.1 Further Analysis of the Problem

To ensure that we fully understood what we could do to maximise the effect of our proposed solution we went to the D-school to unpack and think about the problem from various angles. We began by thinking about the stakeholders involved and how they related to each other. Thereafter, we discussed what type of person Ben was, and what needs we needed to tailor the problem and solution to. We not only analysed what was expressly said but also any deeper implications. Following this we thought 'BIG' to identify possible solutions given no limitations ie unlimited time, unlimited money, and unlimited technology. With all of this in mind, we then thought of multiple realistic solutions, unpacking each advantage and disadvantage associated with our ideas. Subsequently, we used this to combine the best elements of each idea into one final proposed solution.

2.2 Proposed Solution

The proposed solution was to develop a thermal management and monitoring system that consists of a dual power module consisting of a solar panel and a rechargeable battery. The battery voltage will be regulated to voltage levels required by the sensing and cooling submodules, and it will have other protection mechanisms. The cooling module consists of thermoelectric coolers and vents which aim to extract the hot air in the nest's air gap. The mechanical module covers the thermal insulation and structural integrity of the nest. A sensing module will consist of a temperature sensor and humidity sensor triggered by a controller. Data will be reviewed by the controller which will send control signals to the thermoelectric cooler and cooling fan. Data, available for download, will also be sent to the web server module for end use. Using an ESP32 to wirelessly host a webpage for a mobile phone. The webpage will graphically represent the temperature data, and when the thermoelectric cooler was triggered.

2.3 Subsystem Breakdown

Steve - Power System

Will select a battery system and solar panel appropriate to meet the specifications of the other systems. Will also design protection circuitry, regulation circuits and driver circuits.

Talon - Mechanical and Thermal Systems

Will design a revised version of the nest box which incorporates vents, heat transfer methods and thermal insulators whilst maintaining the mechanical integrity of the nest. Will also explore the performance and suitability of thermoelectric cooling systems.

Holly - Interface and Sensing

Will identify a management system suitable for capturing and presenting temperature data. Will also select a temperature sensor and design the user interface which provides downloadable data on a mobile wireless server.

Chapter 3

Literature Review

It takes a great deal of history to produce a little literature.

–Henry James

3.1 Existing Power supply Units

Central to the design of any electrical system is the power supply unit. In a study done by Didik, Jordan, and Iwa [5] to determine the most reliable source of energy between solar energy and wind energy it was concluded that due to the low and inconsistent wind speeds for PV Photovoltaic was an overall better solution the remote areas. That being said this section will focus on the previous work done on solar power supply units.

3.1.1 Design considerations

The work titled 'A water quality monitoring system based on wireless sensor network and solar power supply' [6] explains the utilization of a solar-powered power supply unit in facilitating water quality monitoring alongside a Wireless Sensor Network (WSN). The solar power supply unit was designed to accommodate low power consumption requirements and to ensure adaptability for potential deployment in diverse systems [6].

The system in question supplied distinct voltages of 9V DC and 5V DC, tailored to the varying demands of different subsystems, through the use of a 13.5V, 1.5W solar panel. Notably, the study emphasizes the significance of selecting components characterized by low power consumption. Furthermore, the authors, Ruan Yue and Tang Ying[6] advocate for the integration of an accumulator due to the non-constant nature of sunlight intensity. To stabilize the voltage, a 12V battery was employed, aligning with common practice in solar Power Supply Units (PSUs), as supported by research conducted by Wahyudi and Pandu [2] and Ondrej and Miroslav [7].

A charging regulator was incorporated into the system design for interfacing between the solar panel and the battery, as seen in Fig 1.2. Additionally, the 12V DC output is directed to a power interface circuit, where the conversion to the outputs 9V DC and 5V DC for distinct sub-modules is achieved using linear voltage regulators[6], which shows the importance of having the capability to supply distinct voltages for each subsystem depending on the requirements.

In a complementary study, Wahyudi et al. [2] devised a power supply unit for Zigbee Wireless

Figure 3.1: Solar power system with the interface for battery charging [2]

Sensor Networks intended for operation in remote areas. The design methodology included determining the power ratings of the interconnected sub-modules, which required the parallel connection of two solar panels to meet the system's power requirements. Similar to the work of Ruan et al. [6],[7], considerations were made towards battery capacity selection for backup and voltage stabilization.

3.1.2 Circuit Protection and Weatherproofing

The implementation of an automatic charging mechanism is crucial for prolonging the lifespan of the battery and preventing overcharging [8]. Wahyudi et al.'s [2] study detailed the employment of two transistors to automate the charging process, with the transistors being on when the battery is full and deactivated during the discharge phases. To facilitate transistor control, a regulator resistor was introduced as a limiter. In [9] the importance of weatherproofing the entire system is emphasized as human interaction must be minimised and for the longevity of the electrical components such as sensors which can easily be damaged in a humid environment. They [9] used plastic containers and silicon sealant for weather-proofing which was 86% effective, this demonstrates a promising solution for weather-proofing needs, potentially offering reliable protection.

3.2 Existing Thermal Management Systems

Thermal regulation is a critical practice in wildlife conservation since birds that inhabit warmer climates are subjected to significant physiological changes [10]. The application of existing cooling systems spans various environments due to the wide range of technology available. This section evaluates the performance of the technologies on parameters such as thermal control, energy usage and complexity.

3.2.1 Thermoelectric Cooling (TEC)

Thermoelectric coolers (TEC) are the only commercially available miniaturized cooling systems however the technology has been difficult to integrate ubiquitously due to their low cooling capacity (Z) and coefficient of performance (COP). Historically, the use of Peltier devices (TECs) was explored in electronics thermal management however concerns over decreased system reliability and increased power demands have led to a preference for conventional cooling methods [11]. According to Phelan et al. [11], research has predicted that the efficiency of TECs is likely to improve. Despite the efficiency uncertainty, when compared to conventional compression cooling systems, they are beneficial for reducing environmental impact and can be integrated with solar for smaller-scale applications. Notably, TECs have no moving parts, produce low noise and are reliable in control, rendering them useful for practical applications. Further research showed that TEC optimization can be done to increase COP by cascading TECs together. There is a consensus in the literature that TECs are insufficient for industrial cooling however there is potential in the context of nest thermal regulation.

3.2.2 Vortex Tubes

Vortex tubes span several cooling and ventilation applications due to their complex thermodynamic phenomena. The earliest practical use of vortex tubes gained attention in the 1940s when Rudolf Hilsch found a cheaper alternative to traditional refrigerants for industrial equipment [12]. Since then, alternate forms such as low-pressure vortex tubes have been experimented with in the electronics industry [13].

Due to the only refrigerant being compressed air, vortex tubes provide a safe cooling method when compared to HVAC. Other parameters such as low cost, ease of control and design simplicity, make vortex tubes a favourable technique in the agriculture and medicine industries [14]. Despite attempts to integrate vortex tubes into refrigeration systems due to their pressure reduction capabilities, their low coefficient of performance (COP) renders them impractical as standalone cooling devices [15]. According to experiments done by Kumar et al. [16], low-pressure vortex tubes have a cooling potential of 15°C lower than ambient temperature [16].

Gupta et al. (2017) stated that the inlet quality is a significant factor in the cooling capability of the vortex tube. As a result, foreign particles from the Kalahari terrain deem vortex tubes as an impractical cooling technique. Furthermore, the impact of nest disturbance requires further investigation despite it being a resource-efficient and affordable solution.

3.2.3 Heating, Ventilation and Cooling (HVAC)

Air conditioning is the predominantly used thermal regulation technology with the most effective cooling procedure in commercial and residential applications [17]. Elnagar et al. [17] indicated that mono-split and multi-split make up the two categories of HVAC cooling systems with mono-split more suited to residential use and multi-split suited to commercial use. HVAC systems have a much higher COP as a result of greater power usage [17]. HVAC systems are advantageous when compared to air-cooled condensers due to their non-obtrusive size and enclosed moving parts [17].

[18] conducted an experiment which investigated how lovebirds cooled themselves using mechanical air vents. Lovebirds utilized air vents regardless of footstep traffic and noise however these locations did not become primary nesting spots but merely temporary thermal relief [18]. An important finding illustrates that the photovoltaic system reduces in size by reducing the HVAC load [19].

When compared to TECs and vortex tubes for small-scale applications, HVAC systems are rendered impractical. Although there is a greater COP and no moving parts, HVAC systems are impractical due to the complexity, power usage and toxic coolants.

3.2.4 Passive Cooling Techniques

Passive cooling techniques have seen a steep rise in implementation in developing countries due to it being affordable and simple to implement [20]. Among these techniques, solar shading is accepted as the most straightforward, capable of reducing temperatures by 2°C - 3°C [21]. According to [20], thermal insulation limits heat transfer causing internal temperatures to reduce by a further 4°C - 6°C.

Alternative induced ventilation techniques consist of mechanical systems which make use of thermodynamic principles to transfer heat. Rural India makes use of air vents, radiative cooling and evaporated cooling however these techniques are limited by human intervention and regional conditions [20]. Thermal insulation is the most appropriate passive technique for avian nests as it minimizes disturbances on the birds. Gray et al. [22] found that heavier nests have lower thermal regulation capabilities however thicker insulation walls increase thermal regulation [22]. Although passive techniques have smaller effects on thermal regulation, incorporating these ideas decreases the strain on active solutions.

3.3 Sensing and Data Capturing

In the attempts of wildlife conservation, there exists a growing need for efficient solutions, particularly when human intervention is limited. As the importance of temperature observation increases, a system capable of automatic processing, storage and transmission becomes paramount. This section explores the current techniques of temperature sensing and processing and data storage, delving into the methodologies, challenges, and advancements.

3.3.1 Temperature Sensing

As a result of rapid technological advancements, smart sensors have gained attention due to their independence in processing and transmitting data [23]. According to Meijer et al. [23], industrial sensor use requires thorough calibration and a stable resolution which results in expensive temperature sensors. Smart sensors have enabled integration with voltage conversion circuits and simple connection to micro-controllers [24]. Typically, an analog-to-digital converter (ADC) is required for data processing and transmission, unless the micro-controller incorporates a built-in ADC. Discrete temperature sensors are the predominant sensor device in industrial use due to their excellent long-term stability and high accuracy [23].

Smart temperature sensors were found to perform optimally in the -50°C to 140°C range [23]. However, temperature sensors in warmer climates experience intense calibration drift, material degradation and sensor ageing which decrease the reliability of the recordings [25]. Appropriately matching electronic components can minimize sensor ageing and inaccuracies [23]. Due to the peak performance occurring in a range which coincides with the Kalahari's climate, temperature sensors can be regarded as a reliable measuring technique [23].

3.3.2 Data Acquisition and Processing

Traditional data acquisition and processing consists of three components, the first being SCADA which is the software responsible for control processes, the second being PLCs which are the hardware units which house the control cables and lastly internal connections between the source and dispatch points [26]. AbdelRassoul and Roshdy [26] state that micro-controllers replace PLC and thereby decrease implementation costs and improve execution time. SCADA and PLC systems have typically been used in power stations and other industrial plants [26], therefore system simplification must be done for small-scale applications.

The recognized protocol used for acquiring data involves the MCU providing a sampling signal which collects data, then converting it to a format compatible with the Tx/Rx transmission [27]. Amongst the several microcontroller technologies available, PIC and AVR are the predominantly used protocols as they enhance software integration [26]. AdbelRassoul and Roshdy [26] observed that wireless sensor networks and GSM are the best systems for data acquisition and control in the automation industry as wireless networks remove the cost and complexity of cables. Although these are important factors, further research is required in determining the suitability for micro-level projects.

3.3.3 Data Storage

Currently, the most prevalent storage media found on small-scale electronic equipment are flash memory (SSD/USB), EEPROM and external storage interfaces [28]. However, in recent years, cloud data and distributed databases have changed the perception of data storage [29]. Although cloud data provides ubiquity and dynamic data retrieval, it drastically increases the cost and complexity of low-budget systems. For dedicated purpose systems, static storage is sufficient [30]. The important parameters with these systems are storage size and data reliability [28].

When assessing the different options, various specifications must be considered such as retrieval rate, costs and data integrity [28]. Flash memory was primarily used in embedded systems however in the late 2000s, it made the transition to higher functioning electronics [31]. Flash drives degrade in use after every read/write cycle however the measured life span is typically 100x the manufacturer specifications [32]. Although degradation is unwanted, there are performance algorithms and referencing techniques which minimize the effects [32]. According to Grup et al. [31], these devices serve as robust, high-capacity storage devices for lower-level applications such as storing sensor data.

Embedded processors typically have on-chip memory which eradicates the need for busses and wires [33]. These systems are advantageous due to automatic allocation of data which improves data storage without reducing portability [33]. Similar to Flash, EEPROM is a non-volatile memory device which renders the device useful for systems in unpredictable environments. Unlike Flash, EEPROM has low storage capabilities when compared to Flash and SD storage which requires a consistent transmission of data to a secondary storage source [30].

3.4 Existing Transmission Techniques

Ben requires a cost-effective and non-intrusive method to collect sensor data from the nests without disturbing the Yellow-Billed Hornbills. Traditional wired data transfer or removable storage options are unsuitable as ,over time, the sand in the Kalahari destroys such components. Therefore, this section focuses on exploring wireless data transmission techniques. Wireless transmission allows communication between two devices without a physical link, eliminating the need for cabling. In this case, it offers many advantages; not disturbing the birds, easy installation, no exposed hardware and freedom of connection. This section explores existing transmission techniques that have used Raspberry Pis and Arduino's.

3.4.1 Raspberry Pi

Vujovic and Maksimovic [34] found the Raspberry Pi to be a popular choice when building low-cost environmental monitoring systems and that it has been successfully used in a range of scenarios [34],[35],[36]. They [34] comment that it is a cost-effective and versatile option to communicate with sensors; provides adequate memory to store sensor data, and supports various peripherals.
Vujović and Maksimović [34] integrated the Raspberry Pi as a sensor node in their home automation system, using it in conjunction with a Wi-Fi network to facilitate remote communication of the sensor nodes. Not only that, but they [34] also used it as a processing and control node to fully utilize its features. Furthermore, they [34] expanded the system to use AI to increase confidence in predicting that there was a fire in the building. Overall V. Vujović and M. Maksimović [34] list numerous advantages of using the Raspberry Pi in such applications including processing power, connectivity, memory, high-level languages, community support and cost.
A similar approach to data transmission was taken McBride and Courter [35], whose system monitors birds and collects environmental data remotely. Their [35] system uploaded the data using WIFI to an offsite Raspberry Pi that served as a database. In line with this, Prinz et al,[37] who also used Raspberry Pi computers for woodpecker nest monitoring, explained that, by using a Raspberry Pi computer system and the wireless technology it offers, they were able to 'upload videos to the cloud, alter programs, and troubleshoot problems [all] without removing the units from the woodpecker nests ' [37]. Similarly, Jadhav et al [36] used the Raspberry Pi to implement a web server that fetched real-time data from sensors that could then be accessed by the user through a web browser. Importantly, those who implemented a Raspberry Pi System specifically for bird monitoring noted that the Raspberry Pi data collection did not disturb the birds, provided accurate data and reduced observer effort [35], [37]. However, McBride [35] emphasised the significant power requirements required by Raspberry's Pis. They found that solar panels were not sufficient to charge both the sensors and the Raspberry Pis. There was no further information given about the specifics of the power generation and consumption of the system, but, significantly, this study [35] took place in Ohio during the winter and therefore there were limited hours of sufficient sunlight each day Even so, this important consideration was also mentioned by Vujovic and Maksimović [34]who list the disadvantages of the Raspberry Pi as power consumption and weight.

3.4.2 Arduino

Arduino is another popular option for environmental monitoring as it offers many of the same advantages as the Raspberry Pi. These include simplified integration of analogue sensor notes as well as reliable communication schemes [38]. For instance, an environmental sensing system developed by Zafar et al [39] used the Arduino Uno board to interface with the sensors and uses a WIFI module to transmit collected data through Iot API thingSpeak. Arduino-based solutions offer simplicity and affordability, making them ideal for educational purposes and budget-constrained projects [40]. Their lower power consumption also gives them an edge over Raspberry Pi's [40].
However, when Arduinos are used for environmental sensing they are often used in conjunction with Raspberry Pis as Raspberry Pis are a more popular tool for wireless data communication [38], [41]. In the case of Deshmukh et al [38], the 'Arduino Nano in WSN acts as a medium to the sensor for providing the data to the Raspberry Pi which acts as a base station'. Similarly, in the case of Ferdoush

et al [41], a Raspberry Pi B, Arduino UNO R3 and XBee Pro S2B were used. In this case [41], the Arduino was connected to the sensors and communicated through XBee to the Raspberry Pi, which was used as a base station with a web application for users to interface with the system.

3.5 Literature critique and conclusion

The existing research shows that there is great research in the field, but not specifically in bird nest cooling. This is because the literature lacks sufficient focus on solar power's suitability for more demanding applications like cooling systems. Additionally, most studies concentrate on indoor or controlled settings, potentially overlooking the unique challenges of desert environments such as high temperatures, sand, and other factors which could significantly affect the performance and longevity of solar-powered equipment. Although the reviewed literature covers wireless transmission methods specifically for bird monitoring, a broader exploration is necessary since Ben's project encompasses different wildlife. The analysis of cooling systems highlights varied options, each with its advantages and drawbacks in the context of Southern Yellow-Billed Hornbill conservation. The complexity, noise levels, cooling capacity, and cost of each system need careful consideration when choosing an optimal solution.

In conclusion, the power module's design is greatly determined by the type and specifications of the cooling system. Although HVAC systems provide high COP for thermal regulation, the power requirements rule it out as a feasible option for the conservation project. When comparing vortex tubes and TECs, the deciding factor is the disturbance caused by the constant air circulation. Despite TECs' relatively high power usage, they are the most suitable system to adapt to the project as there is little environmental disturbance and ease of control. Additionally, both the Raspberry Pi and Arduino present themselves as possible solutions. The Raspberry Pi stands out due to its ease of use, robust processing power and connectivity options while the Arduino is a cost-effective and power-efficient option. Arduino's compatibility with wireless transmission modules like XBee enables integration with Raspberry Pi, offering a combined solution that utilizes the strengths of both platforms but also increases the cost and complexity.

Chapter 4

Power Submodule - MHLSTE012

4.1 Introduction

The design of a power sub-module is crucial in ensuring the seamless operation of any cooling system. This chapter aims to present the design process, planning and implementation of the power sub-module aimed at providing regulated voltage to two critical sub-modules, namely the front end and sensing sub-module which uses the ESP32 microcontroller, and the cooling sub-module, powered by the Peltier TEC. The chapter presents the user requirements derived from stakeholder engagement and the functional and design specifications derived from the user requirements in a traceability matrix. The power requirements from the other sub-modules are used to make optimal design choices for the battery capacity, the solar panel, the suitable protection and charging circuits, and the appropriate interface ports for the design.

4.2 System Requirements and Specification Analysis

This section presents the user requirements which are IDed by UR**x**, the functional requirements labelled by FR**x**, and the design specifications labelled by DS**x**.

4.2.1 User Requirements

UR1	**Reliability**
Requirement	The power subsystem must be reliable
Justification	The overall aim of this project is to provide adequate cooling to the nest, and to achieve this the power supply unit must be reliable and robust.
Refined by	UR1:FR1(Circuit protection), UR1:FR2 (Charging circuitry),UR1:FR3(Driver circuitry), UR1:FR4(Voltage regulation circuitry)
Verifications	ATP1, ATP2,ATP3, ATP4 ,ATP5, AT6,ATP7

UR2	**Subsystem Intergration**
Requirement	The PSU must be designed with integration for simple integration with other submodules
Justification	The power supply unit must easily integrate with the other subsystems through interface ports
Refined by	UR2:FR1 (Ports & Screw terminals)
Verifications	ATP8

4.2.2 Functional Requirements

The following traceability matric tables present the functional requirements for the PSU.

UR1:FR1	**Circuit Protection**
Requirement	The power supply must be protected from weather conditions, overcharging and overcurrent.
Refines	UR1
Refined by	UR1:FR1:DS1(Weather proofing enclosure), UR1:FR1:DS2: (Overcharge protection); UR1:FR1:DS3:(Overcurrent protection).
Verifications	ATP1, ATP2,ATP3

UR1:FR2	**Charging circuitry**
Requirement	The power supply will be solar powered thus a charging circuit for the battery is required.
Refines	UR1
Refined by	UR1:FR2:DS1 (Solar Charging Circuit)
Verifications	ATP4

UR1:FR3	**Driver circuitry**
Requirement	The thermoelectric cooler requires an automatic switch for controlling its input voltage thus a driver circuit is needed.
Refines	UR1
Refined by	UR1:FR3:DS1 (Driver circuit)
Verifications	ATP5

UR1:FR4	**Voltage regulation circuitry**
Requirement	The PSU must be able to supply constant DC voltages to the cooling system, sensing and data monitoring subsystems.
Refines	UR1
Refined by	UR1:FR4:DS1 (Voltage Regulator Circuits) & UR1:FR4:DS2 (Buck Convertor Circuit)
Verifications	ATP6,ATP7

UR2:FR1	**Subsystem Interface**
Requirement	The PSU should supply the desired voltages to the cooling system, sensing and data monitoring subsystems.
Refines	UR2
Refined by	UR2:FR1:DS1(USB Ports & Screw terminal block)
Verifications	ATP8

4.2.3 Design Specification

Derived from the functional requirement the following traceability matrix presents the design specification.

UR1:FR1:DS1	**Weather proofing enclosure**
Specification	The enclosure should be designed to the size of the PSU and have the necessary cutout for USB A connection, screw terminal block for the solar panel and the thermoelectric coolers.
Refines	UR1:FR1
Verification	ATP1

UR1:FR1:DS3	**Overcurrent Protection**
Specification	Using current limiting resistors & other components, the PSU should have acceptable current levels. The components for the power supply unit should be selected to meet the design specification so it doesn't draw more current from the battery and solar panel.
Refines	UR1:FR1
Verification	ATP2

UR1:FR1:DS2	**Overcharge Protection circuit**
Specification	Using a type of switch the circuit should automate the charging process to be on when not full and off when fully charged and indicate when in charging mode.
Refines	UR1:FR1
Verification	ATP3

UR1:FR2:DS1	**Solar Charging circuit**
Specification	The circuit should charge a 12V,7.2Ah battery from a solar panel variable voltage.
Refines	UR1:FR2
Verification	ATP4

UR1:FR3:DS1	**Driver circuit**
Specification	The circuits should output a switchable 8V to the TEC.
Refines	UR1:FR3
Verification	ATP5

UR1:FR4:DS1	**Voltage Regulator**
Specification	The circuits should regulate a 12V from the battery to 5V for the Thermoelectric Cooler and 5V for the microcontroller.
Refines	UR1:FR4
Verification	ATP6

UR1:FR4:DS2	**Buck Converter**
Specification	The buck converter should convert the 12V from the battery to 5V for the SD card reader module.
Refines	UR1:FR4
Verification	ATP7

UR2:FR1:DS1	USB Ports & Screw terminal block
Specification	The regulator circuits should output the required voltage and interface with the MCU via a USB port and the cooler via a screw terminal block.
Refines	UR2:FR1
Verification	ATP8

4.3 Design Process

This section outlines the design choices made for the component selection, circuit designs and comparisons.

4.3.1 Solar Panel Selection

For the selection of the solar panel, a detailed analysis of the submodule components' typical operating power consumption calculations was performed and are presented in the table (4.1).

Since the system will not be operating in the theoretical maximum power consumption the solar panel

Submodule Component	Op.Voltage (V)	Op.Current	Op. Power(W)
Temperature and Humidity Sensor	6	1.5 mA	0.01
ESP32 Wifi Dev Board	3.6	80 mA	0.29
Two TEC	8	1.6×2 A	25.60
SD Card Module	5	80 mA	0.40
Total Power	-	-	**26.30**

Table 4.1: Operating Power Consumption Calculation

wattage has to be greater than 26.30W and with a voltage of at least 8V input voltage to ensure the battery to be selected can be charged quicker. From these theoretical power consumption, the following solar panels are compared in table 4.2.

Solar	Ratings(Wattage, Voltage, Current)	Price	Type
https://shorturl.at/irMTY	20W, 17V, 1.14A	R430	Monocrystalline
https://shorturl.at/dmzP5	30W, 18 V,1.66A	R600	Monocrystalline
https://shorturl.at/bozCQ	40W, 17.7V, 2.3A	R500	Polycrystalline
https://shorturl.at/gmoHN	10W, 18V, 0.55A	R299	Monocrystalline

Table 4.2: Solar Panel Comparisons

Monocrystalline solar panels are crafted to maximise efficiency but at a higher cost. Polycrystalline panels, on the other hand, offer a more affordable option with slightly lower efficiency with higher power ratings. The maximum current to be drawn from the battery is 1.6A and to avoid operation near the theoretical maximum, the 40W, 17.7 at 2.3A solar panel is chosen for the design.

4.3.2 Battery Selection

The system should function even when the light intensity is low thus a high-capacity battery should be selected for this application. Several rechargeable battery types are considered before the selection of the capacity.

Battery Type Selection

There are a lot of battery types, and form factors for different applications but we will only focus on the more accessible types. Alkaline Batteries are mostly not rechargeable, have a small battery capacity and are costly. The lithium-ion batteries offer both rechargeability and high capacity but with a steep price tag for the higher capacity. Although connecting more batteries in parallel will result in higher capacity, the voltage remains the same, which will typically be lower than 8V for affordable lithium-ion batteries. The lead-acid batteries are rechargeable, cheaper and have high capacity while performing well in high temperatures as the batteries are commonly used in cars as well. The solution is to use lead-acid batteries as the cooling system requires a lot of power and will be used in Kalahari which is a high-temperature area.

Battery Capacity Selection

Table 4.3 compares the different capacities of the lead-acid batteries for the selection of an adequate capacity. The battery life is calculated using the estimated operating power consumption from table 4.1 using equation (4.1).

$$BL = \frac{B_{capacity}(Wh)}{P_{operating}(W)} \tag{4.1}$$

Where BL is the battery life in hours, $B_{capacity}$ is the capacity of the battery and $P_{operating}$ is the estimated power consumption.

Battery URL	**Ratings (Voltage, Capacity)**	**Price**	**Capacity (Wh)**	**Battery Life (hours)**
https://shorturl.at/koYZ1	12V, 2Ah	R200	24	0.91
https://shorturl.at/wFRS0	12V, 4Ah	R167	48	1.83
https://shorturl.at/kAFJ4	12V, 4Ah	R206	48	1.83
https://shorturl.at/cemzU	12V, 7Ah	R195	84	3.19
https://shorturl.at/fowJ3	12V,7.2Ah	R230	86.4	3.29

Table 4.3: Lead Acid Battery Capacity Comparisons

From table 4.3, the battery which will last longer when the system is using exactly the theoretical operating power is the 86.4Wh battery which can last 3.29 hours on a single charge. This is very important because the power supply should provide power without human intervention. Looking at the price differences between the batteries, the 12, 7.2Ah battery with higher capacity is selected as the optimal battery of choice for this power supply unit.

4.3.3 Buck Converter Design

To convert the 12V from the battery to a constant 5 DC for the SD card reader module, three possible choices are linear voltage regulators, adjustable voltage regulators and a buck converter.

Solutions Comparisons

Linear voltage regulators provide a straightforward approach for converting 12V to 5V, offering simplicity and low noise but with significant energy loss as heat. Adjustable voltage regulators offer versatility, allowing fine-tuning of output voltage, resembling a customizable valve system catering to specific needs while still dissipating excess energy as heat. Meanwhile, a buck converter efficiently transforms 12V to 5V by switching the input voltage, minimizing energy loss and maximizing efficiency. Due to its efficiency, the buck converter is chosen for this application.

Converter Value Calculations

The table 4.4 summarises the calculated values for the buck converter calculated using equations 4.2, 4.4, and 4.3, the switching frequency f_s was selected at 75kHz and the output voltage ripple ΔV selected at 0.01 to result in a close to constant DC voltage, the resistor $R = 62.5\Omega$ which represents the SD card module using it's rated V&I ratings.

Converter Value	**Calculated Value**	Equation Used
Duty Cycle	0.417	$$D = \frac{V_o}{V_{in}} \tag{4.2}$$
Inductor Value	$78\mu H$	$$L = \frac{R(1-D)}{2f_s} \tag{4.3}$$
Capacitor Value	$4.1\mu F$	$$C = \frac{1-D}{8L(\frac{\Delta V}{V_o})f_s^2} \tag{4.4}$$

Table 4.4: Buck Converter Calculated Values

The circuit in figure 4.1 presents the designed buck converter circuit.

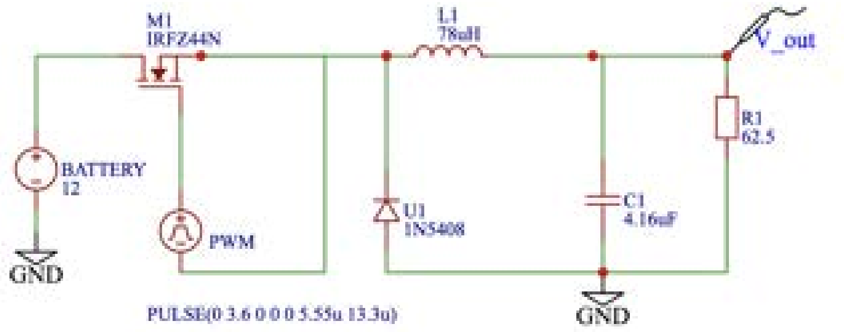


Figure 4.1: Buck Converter Circuit

The IRFZ44N MOSFET has a R_{on} of 17.5$m\Omega$ and switch loads up to 55V and 49A. The IRF740 N-Channel Power MOSFET which can switch power loads up to 400 V and 10 A, this MOSFET has a R_{on} of 0.55Ω. The IRFZ44N is chosen as it can switch loads up to 55V and is suited for high switching frequency applications because of the low R_{on} which means lower energy losses. 1N5408 diode was chosen for this application as it can allow up to 3A of current to pass through compared to the 1N5399 diode which can only handle up to 1.5A.

4.3.4 Charging Circuit and Protection

Since the charging circuit will be getting the voltage from the solar panel which has a fluctuating voltage a circuit to charge the battery using solar is required.

Solutions Comparisons

To charge the battery from a variable source a maximum power point tracking (MPPT) charger circuit can be used this advanced circuit type dynamically adjusts the voltage and current from the solar panels to ensure maximum power transfer to the battery. A simple charge circuit regulates the voltage from the solar panels to prevent overcharging the battery, usually employing a shunt regulator or series regulator. Pulse width modulation (PWM) charge circuit regulates the charging by switching the connection between the solar panels and the battery, controlling the charging current. The simple charger circuit is chosen because of its simplicity and low cost compared to more complex charge circuit designs like MPPT or PWM. The charging circuit has overcharge protection which meets two design specifications namely UR1:FR2:DS1 & UR1:FR1:DS2.

Circuit Design

The TL431 shunt regulator is chosen instead of the LM317T because it has more voltage referencing precision and requires fewer components which can lead to lower overall system cost, reduced board space which can be sustainable in the long run, and easier circuit design and assembly. The IRF740 N-Channel Power MOSFET which can switch power loads up to 400 V and 10 A, this MOSFET has a R_{on} of 0.55Ω. The IRFZ44N MOSFET has a R_{on} of 17.5$m\Omega$ and switch loads up to 55V and 49A. The IRF740 is chosen as it can handle higher voltages making the charger circuit more versatile and the IRFZ44N is more for application of high switching frequencies.

The IRF740 MOSFET facilitates overcharge protection by taking in the adjusted voltage from the TL431 and switching based on the reference voltage from the battery. Overcharge protection can be visualised by the user when needed by the LEDs which indicate a green when fully charged and red when the battery is charging. The 1N5408 diode is to prevent charge from flowing from the battery to the charging circuit thus wasting power by keeping the LEDs on while not charging. This diode was chosen for this application as it can allow up to 3A of current to pass through compared to the 1N5399 diode which can only handle up to 1.5A. The charging circuit can take 4V to 14V and charge when the solar voltage is greater than the battery's voltage.

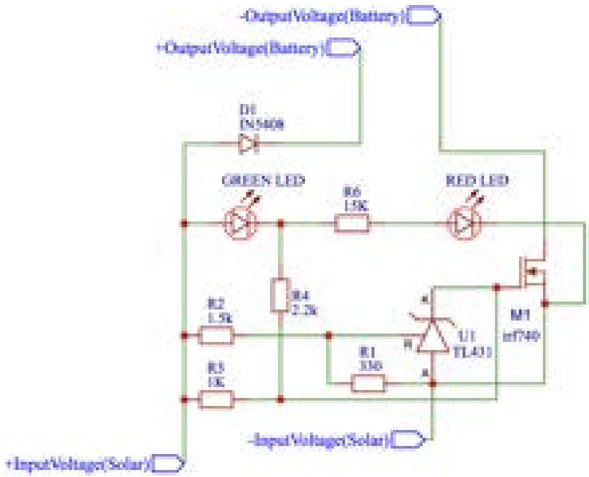


Figure 4.2: Automatic Charging Circuit

4.3.5 Circuit Weather Proofing

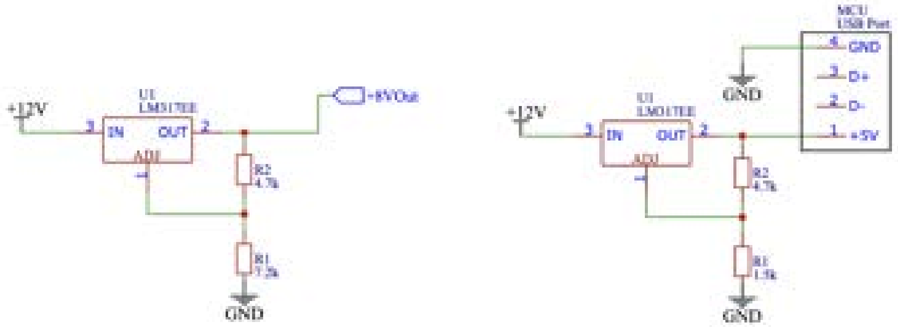
The circuit should also be protected from weather conditions as justified in UR1:FR1:DS1. Autodesk Fusion 360 was used to design the circuit enclosure for protection under moist conditions. The figure in Appendix C.2 presents the enclosure for the battery and all the circuits. The circuits fit on a 93mm by 145mm Veroboard thus the parts are designed to cover that area.

4.3.6 Interface Circuits and Voltage Regulation

To supply the power to the different submodules there needs to be regulation from the 12 V battery voltage to the different modules.

Microcontroller Unit & Thermoelectric Cooler (TEC) interface

The microcontroller unit (MCU) of choice comes with a USB A cable thus the power will be regulated to 5V which will be taken by the MCU and regulated down to the operating voltage of 3.6V by the onboard regulator. Adjustable voltage regulator circuits are used for the application as the buck converter although efficient is bucky, was used for the SD card model and would incur more compared to the LM317T regulators. Figure 4.3 presents the circuitry for the MCU circuit which has a port for the USB A cable for interfacing with the MCU. The TEC requires an 8V input voltage and it will need to be interfaced with the driver circuit which will act as a switch based on the temperature measured from the sensing module.



(a) TEC Voltage Regulation circuit

(b) MCU Voltage Regulation Interface circuit

Figure 4.3: Interface Circuits

4.3.7 Driver Circuit

To drive the voltage or control the voltage going to the TEC to as per the design specification UR1:FR3:DS1. Since the TEC requires an automatic switch to save power, the life span of the coolers by only turning it on when needed, a switch is used for this application as the MCU can not provide the required 8V at 1.6A.

Solutions Comparison

BJTs, MOSFETs, and IGBTs are some of the possible switches for the driver circuit. BJTs are current-controlled devices, meaning the amount of current flowing into the base terminal controls the current flow between the collector and emitter. They are mainly used for low-power applications. MOSFETs are voltage-controlled devices, where the gate-source voltage controls the current flow between the source and drain terminals. They are widely used in power electronics due to their high input impedance, fast switching speeds, and low power consumption in the off state. IGBTs are a hybrid of BJTs and MOSFETs. Since MOSFETs are voltage-controlled and have a lower R_{on} resulting in lower power losses, a MOSFET is selected as a switch for this application.

Circuit design

The circuit in figure 4.4 provides the interface to the TEC and uses a microcontroller signal of 3.6V which is used to turn on the gate of the MOSFET. For this application since the gate signal is 3.6V the IRFZ44N MOSFET is used as it can take the low signal from 2V to 4V (gate threshold voltage) and is suited for high-frequency switching compared to the IRF740 MOSFET. A pulldown resistor of $10k\Omega$ is used to mitigate small noise from turning the gate of the MOSFET on.

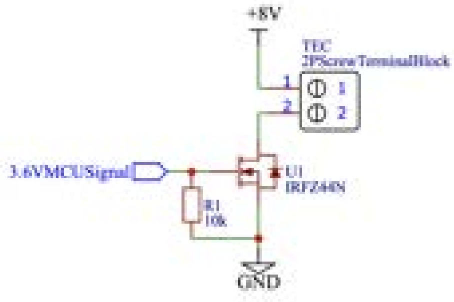


Figure 4.4: TEC Driver Circuit

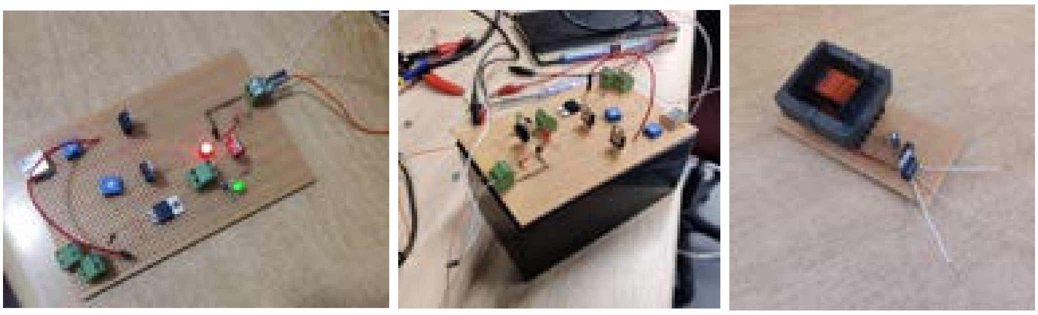
4.4 Prototype Testing

4.4.1 APTs for Subsystem

APT Label	Description	Refines
ATP1	Enclosure should protect circuit from water, moist etc	UR1:FR1:DS1
ATP2	Current drawn when charging from the power supply should not be more than 100mA	UR1:FR1:DS3
ATP3	The circuit will be tested by leaving it stay till the voltage excesses the maximum voltage of 13.1V which will be a fail case or indicates it is no longer by the turning on of the green LED with a measured battery voltage of 13.1V	UR1:FR1:DS2
ATP4	The charging circuitry should be subjected to variable DC voltages to emulate the solar voltage and must charge from a 12V to 17V voltage range	UR1:FR2:DS1
ATP5	A 3.6V signal generator pulse will be used to simulate the pulse from an MCU which will be the turn-on and of signal from this signal an 8V output is expected when the pulse signal is high and 0V is expected when the signal is low.	UR1:FR3:DS1
ATP6	Both regulator circuits must be supplied with a 13.1 V from the battery and must regulate to 5V for the microcontroller and 8V for the thermoelectric cooler with an acceptable voltage deviation of $\pm 0.2V$ for both regulators	UR1:FR4:DS1
ATP7	The buck converter when the input voltage of 13.1 from the battery is input buck convertor should output a 5V with voltage variation of $\pm 0.2V$	UR1:FR4:DS2
ATP8	The power subsystem USB A and Screw block terminals must output the excepted 5V and 8V output voltage.	UR2:FR1:DS1

Table 4.5: Subsystem APTs

The circuits were simulated on LTSpice and soldered on a Veroboards of dimensions 145mm by 93 mm and assembled, the final prototypes can be seen in figure 4.5.



(a) Cascaded Circuits Forming the full Subsystem

(b) Charging Circuit Mounted To Battery

(c) Buck Converter

Figure 4.5: PSU Prototype

4.4.2 Buck Converter Testing

The buck converter circuit was connected as shown in Appendix C.1, the buck converter PWM used was a 12V, 41.6% duty cycle since the 3.6V PWM from the signal generator could not turn on the IRFZ44N MOSFET thus MOSFET driver circuit will be required when the PWM signal is output from the microcontroller. The results in Appendix C.1 present the PWM used from the signal generator which emulates a PWM from a microcontroller along with the result for the output voltage.

4.4.3 Charging Circuit Testing

The charging circuit was connected as in figure 4.2 and subjected to varying DC voltages. The results in figure C.3 depict it can charge with a 12V DC, the charging circuit draws 100mA from the power supply. The battery was kept plugged in to see the change in the battery voltage, the voltage increased from 11.7V to the actual maximum of 12.76V. The charger circuit was tested for the DC voltage ranges from 11.9 to 13.8V and as long as the battery was below the solar voltage it could charge.

4.4.4 Driver Circuit Testing

The 3.6V voltage expected from the microcontroller was generated using a signal generator and the regulated 8V from the voltage regulator circuit was used as per the results in figure 4.6 the driver circuit provided an 8V for an input signal voltage of 3.6V and 0V for no signal.

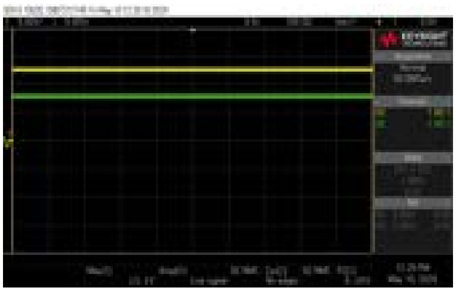
(a) 3.6V Signal Generator Pulse

(b) Driver Circuit Output Voltage

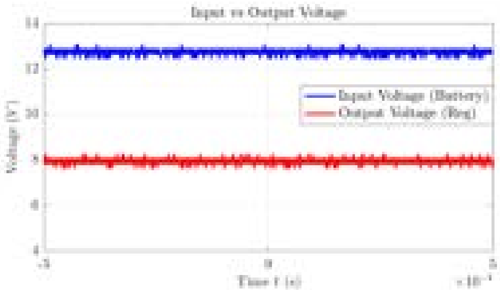
Figure 4.6: Driver Circuit Measured Results

4.4.5 8V Voltage Regulation Test

The DC voltage data from the oscilloscope was saved as a CSV file and plotted using Matlab to analyse the variations in the output voltage. Figure 4.7 depicts a less than 0.2V deviation in the output voltage from the expected 8V.



(a) Oscilloscope Result



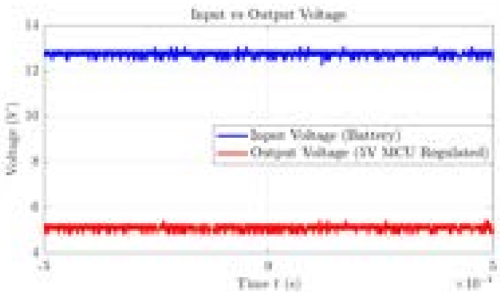
(b) TEC Plotted Result

Figure 4.7: TEC Measured Results

4.4.6 5V Voltage Regulation Test

The 5V regulator circuit was connected to the 12V from the battery separate from the other circuits and integrated with the other circuits the results measured from the oscilloscope and plotted can be seen in figure 4.8. The regulator circuit outputs a 5V as expected from taking a 13.1V input voltage from the battery and the voltage ripple was less the 0.2V.

(a) Oscilloscope Result



(b) 5 Volt Regulator Circuit Plotted Result

Figure 4.8: PSU Prototype

4.4.7 Ports Testing

The ports and terminal screw blocks were tested and the results indicate they output the expected voltages. Figure 4.9 depicted a load connected to the 5V USB port intended for the microcontroller.

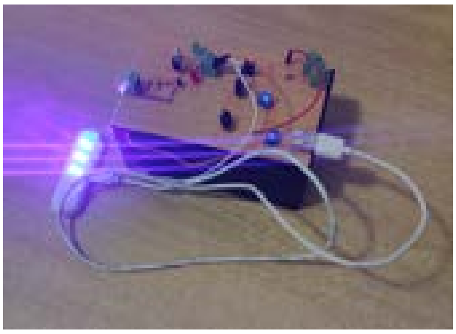


Figure 4.9: USB functionality test with 5V UV light load

4.4.8 APT Results

APT Label	Test Result	Comment
ATP1	Marginal Fail	Enclosure was not printed in time to evaluate ATP
ATP2	Passed	The current drawn from the DC power supply was 0.01A
ATP3	Passed	The solar battery charger automatically turns green when the battery voltage terminals read 12.76V.
ATP4	Passed	The charging circuit can charge from 11.9V to 13.8V when the battery voltage is less than the range.
ATP5	Passed	The circuit outputs the expected 8V when the signal is 3.6V and 0 when the signal is 0.
ATP6	Passed	Voltages have output deviation of less than 0.2V
ATP7	Marginal Pass	Buck converter outputs voltage is within $5 \pm 0.2V$ but this was achieved when the signal generator emulated pulse was at 12V instead of 3.6V
ATP8	Passed	The measured voltages on the USB A port and screw terminal were within the $\pm 0.2V$ from the desired values of 8V & 5V

Table 4.6: Subsystem ATPs Results

4.5 Chapter Summary and Recommendations

In conclusion, the PSU has met the prescribed Acceptance Test Procedures (ATPs), although with some marginal passes after modifications, as detailed in Table 4.6. However, the evaluation of ATP1 could not be concluded as the parts could not be printed in time. To improve the PSU design, incorporating a MOSFET driver for amplifying the 3.6V output from the microcontroller unit to drive the MOSFET gate is recommended. Additionally, integrating an optocoupler to isolate the high-voltage side from the low 3.6V MCU output can protect against over-voltage incidents. These modifications offer potential enhancements to the PSU's functionality and safety, aligning it more closely with operational requirements. Further refinement and experimentation by these suggestions can optimize the PSU's performance and reliability.

Chapter 5

Thermal Regulation and Enclosure Subsystem SWNTAL001

5.1 Subsystem Introduction

The thermal regulation of the habitat is central to the conservation efforts and the study of breeding attempts for the Southern Yellow-billed Hornbills. This sub-module consists of the mechanical design of the habitat and thermal regulation methods used to improve breeding conditions. This chapter starts by outlining the user requirements and mapping them to the functional requirements and design specifications. Furthermore, the requirements and specifications will be reviewed using physical tests and simulations. All the design considerations will be discussed and a final solution will be presented and reviewed in the conclusion.

5.2 System Requirements and Specification Analysis

The following subsections will define the user requirements, outline functional requirements and detail design specifications.

5.2.1 User Requirements

The following table details the ornithologist's requirements.

Label	**User Requirement**
UR1	New nests cannot be completely rebuilt as there is no budget to rebuild nests and rebuilding the nests causes the birds to be displaced.
UR2	The birds' habitat must not be disrupted since they will leave the nest if it does not replicate their typical nesting conditions.
UR3	The design must blend in with the environment otherwise the nest would not look like a viable habitat to the birds.
UR4	The internal nest temperature must be below 35°C to improve the breeding conditions.
UR5	The nests must be strong to survive extreme conditions avoid degradation.

Table 5.1: Table of User Requirements

5.2.2 Functional Requirements

The following table details the system's functions.

Label	Functional Requirement
UR1:FR1	The new design must be modular and integrate the fundamental features of the old nest design.
UR2:FR1	The nest must be free of foreign because the hornbills will deem the nest to be an unsuitable habit and find a new nest.
UR2:FR2	The cooling system must not have components that cause noise and low-frequency vibrations.
UR3:FR1	Protruding components and cables must be concealed to prevent choking hazards and the risk of electrocution.
UR3:FR2	The nest's external shell must follow the appearance of the trees in the Kalahari.
UR4:FR1	The active cooling system must be activated when the internal nest temperature exceeds 35°C.
UR4:FR2	The ventilation and passive cooling system must constantly extract excess heat without filtering dust into the nest.
UR4:FR3	The thermal insulators of the nest must have low thermal conductivity to prevent heat from entering the nest.
UR5:FR1	The nest must be able to support the load of a solar panel. It must also have good structural integrity to protect the nest from extreme weather conditions and unexpected hazards.

Table 5.2: Table of Functional Requirements

5.2.3 Design Specifications

The following table presents the final design specifications.

Label	Specifications
UR1:FR1:DS1	The inner layer must be 50cm x 25cm x 21cm with a 5cm diameter hole for feeding. The outer layer must be 50cm x 28cm x 25cm with a 5cm hole in line with the internal hole. Additional features must be modular with the existing design and dimensions. The outer thickness of the wood must be a minimum of 9mm and the internal thickness a minimum of 4mm.
UR2:FR1:DS1	The inner layer must be made of plywood with no sensors below the eye-line of the birds.
UR2:FR2:DS1	The birds are sensitive to sound in the range of 1Hz - 4kHz therefore electronic humming must be attenuated in this range.
UR3:FR1:DS1	System must be waterproofed with effective cable management.

UR4:FR1:DS1	The TEC must be supplied with 6V and 1.5A during its on-state. It must have a duty cycle of 75%. The low-current, heat-dissipating fan must be operated with the same duty cycle as the TEC.
UR4:FR2:DS1	Vents must be covered by fine thread mesh with a minimum of 16x16 mesh count per inch. Vent covers must be angled at a minimum of 15° to the horizontal to dispose of hot air.
UR4:FR3:DS1	The minimum thickness of the damping membrane is 4mm. The fibreglass must be an A grade. Stainless steel nails and screws must be used to prevent rust.
UR5:FR1:DS1	The nest roof must support a solar panel of 8kg.

Table 5.3: Table of Design Specifications

5.3 Design Considerations

The nest box plays an integral part of thermal regulation therefore extensive analysis was done to evaluate the design choices in the nest. The following sections will detail the rationale and technical information behind the decisions.

5.3.1 Active Cooling

The choice of the cooling system required was dependent on the amount of cooling required in the nest. Using the equation $Q = Mc\Delta T$, the amount of energy required to cool down different components of the nest was found. M is the mass of the component, c is the specific heat and ΔT is the difference in temperature after removing the energy. Note that the mass of air was approximated by using the density formula $\rho = \frac{M}{V}$.

Component	Specific Heat (J/kgK)	ΔT	Mass (kg)	Q (J)
Bird	3500	15	0.2	10500
Air	1005	15	3.879×10^{-5}	0.58
Nest Walls	2000	15	3.025	90750

Table 5.4: Table computing the amount of energy required to cool each component by 15° C

The total amount of energy required amounted to 101250.5J which is equal to 28.125W over an hour. The total was split into two forms of cooling active and passive using a 60/40 split. Since the wattage required from active cooling was 16.8W, the suitable arrangement found was to use 2 Peltier devices, each supplying 8.4W.

Two different active cooling methods were considered, namely, thermoelectric coolers and refrigerant radiator compressor systems. Refrigerant systems use a compressor to compress a refrigerant vapour causing its temperature to rise which is pumped into a condenser which dissipates the heat and condenses the vapour into a liquid. The cold liquid enters the evaporator which then extracts heat from the surroundings [42]. Alternatively, thermoelectric systems offered cooling by changing the temperature on the two plates due to the movement of electrons from the different junctions. Refrigerant systems offer great cooling potential due to the dedicated stages in the process however it is not a viable system due to the cost, complexity, energy usage and environmental risk. Thermoelectric coolers also require a large amount of energy however it is a plausible system due to the lack of moving parts, zero noise pollution and simplicity to implement. Various thermoelectric coolers were considered below. Note that the hot side reference temperature was 27°C.

Module	Voltage (V)	Current (A)	Price (R)	Power (W)
ETH-071-14-25-S-H1	6.2	3	244	12
ADV-127-135200-S	7	2.5	180	14
TEC1 12703	6.5	2.2	85	12

Table 5.5: Table showing the different TEC options available

All three modules considered provide the necessary power required for heat removal however the first two choices come at a greater cost than the TEC1 as well as only being available at international stores. Due to the time constraints and costs, the TEC1 is the best option for the project. Two Peltier devices allow for even cooling for a greater amount of area. The amount of Peltiers that can be used is restricted by the power requirements as one device uses the majority of the power supply.

Crucial to the performance of Peltier devices are heat sinks [43]. The performance of the Peltier device's cold side degrades as the hot side temperature passes its rated threshold, therefore heat sinks are required to dissipate the surplus heat. Aluminium fin heat sinks provide a path for heat dissipation due to their thermal conductivity and shape [44]. Since the hot side of the Peltier device can reach temperatures above 60° C, a low-current fan provides further heat dissipation, disposing of the heat from the heat sink. Heat sinks are also advantageous in spatial thermal regulation, a heat sink on the cold side can be considered as a method of radiating the cold temperature to the nest walls [45].

5.3.2 Passive Cooling

Material Selection:

Improving the internal layer's thermal conductivity allows for better absorption from the Peltier's cold side. Methods such as plasma treatment and embedding conductors in the wood achieve this however these methods are not feasible due to the complex equipment required. Soaking the wood in a conductive polymer is a cost-effective method to improve the thermal conductivity of plywood. The process involves drying the wood to remove the air pockets, submerging the wood in a conductive polymer solution and lastly drying the wood to remove the excess solvent. It is essential to select a non-toxic water-based solvent as other options will be hazardous to birds [46].

EPDM (Ethylene Propylene Diene Monomer) is a good thermal insulator and provides waterproofing. The increased thermal insulation prevents heat from entering the nest. There is a drawback however as the increased thermal insulation may trap heat should the internal nest temperature reach high levels.

The added benefit of EPDM is that it provides humidity protection and maintains the plywood's thermal insulation. Water soakage fills the air pockets in wood and water has a higher thermal conductivity than air therefore degrading the thermal insulation properties of wood. EPDM is non-toxic due to its chemical composition however it requires treatment due to strong fumes. Fibreglass is an alternative for thermal insulation. Its structure captures pockets of air which decreases the thermal conductivity. The fibrous structure prevents effective water-proofing however and can result in water soakage. The microfibers in the material may cause disruption in the nest and if ingested may damage respiratory systems. However, the positioning of the material may minimize the release of microfibers.

Thermal Insulators		
Material	Fibreglass	EPDM
Thermal Conductivity	0.36W/mK	0.29W/mK
Waterproofing	Weak	Strong
Cost	Low	Low
Toxicity	Potentially Irritating	Non-Toxic, Requires Treatment

Table 5.6: Table showing the different properties of Thermal Insulators

EPDM provides both thermal insulation and waterproofing whilst being cost-effective and requiring simple treatment making it the best choice for an insulating layer between the outer layer's wood. The risk of using EPDM was that the thermal insulation would be too high and heat the box up. This can be countered by ensuring a sufficient ventilation system is used.

Ventilation: According to the ornithologist, the nest's internal temperatures reach 50°C. This is due to the intake of heat and the lack of heat sinks and vents to expel the heat. Using the principles from convention, hot air rises. As a result, vent holes should be placed close to the roof of the nest box on the outer layer to dissipate hot air. As a result, the hot air will be expelled thus cooler air will be sunk in, continuing the convention process until an ambient temperature is reached. Since the opening to the internal layer is high up on the front of the nest, vents must be placed lower down than the ideal position. A vent at the back of the next allows a flow of air from back to front. Utilizing vent holes results in dust entering the nest requires maintenance over time. As a result, they are accompanied by vent covers that are angled upwards to the horizon to prevent wind from blowing dust into the vent thereby minimizing the dust intake.

The Kalahari experiences good wind speed therefore external vents allow for airflow in the nest's air gap. The air intake scoop vent is one of the vent options for the nest box as shown in Figure A.1 in Appendix A. It captures moving wind and directs it into the nest. Due to the large surface area of the vent face, it has the potential to circulate a large amount of air into the nest. However, it is better suited for moving objects since wind is required to flow in the direction of the vent holes. The alternative is a whirling vane vent, as shown in Figure A.2 in Appendix A, which uses a rotating turbine to capture wind flow and redirect it into the nest. Due to the 360° blades, the vent is not restricted by the direction of the wind flow. When compared to the air intake scoop, the whirling vane vent captures much less airflow. In the context of nest air circulation, too much movement of air results in some high-speed air entering the internal chamber and disturbing the bird. Both vents are prone to dust buildup however due to the design being modular, maintenance is simple. As a result of the controlled air circulation and lack of reliance on wind speed direction, whirling vane vents provide a passive method to sink air into the nest. Four vents on each vertex on the roof would allow for a greater capacity of airflow into the air gap. Anti-parallel fins for the corresponding sides prevent the hot air from circulating in the air gap.

5.3.3 Mechanical Design

Primary Material:

Due to the project's cost constraints, plywood, chipboard and hardboard were the only viable options. The following table details the properties of the materials and includes the properties of acacia wood which is the most common wood found in the Kalahari. Note the comparison was made with all the materials being a 6mm, 2440 x 1220 sheet.

Material	Price	Availability	Hardness
Acacia	N/A	Not Locally	Strong
Plywood	341	Locally	Moderate
Hardwood	821	Locally	Strong
Chipboard	651	Locally	Weak

Table 5.7: Table showing the different wood types available

Chipboard was removed as an option since it is the weakest material whilst being an expensive option. Although hardwood is stronger than plywood, the cost factor outweighs the difference in strength. The strength of plywood can be increased by combining layers therefore it is a suitable option.

Layer Configuration: The existing nest box makes use of 2 layers with an air gap between the layers. Increasing the thickness of the wood improves the insulation capabilities and improves the mechanical integrity. Adding an additional sheet on each face on the outside increases the thickness whilst maintaining the air gap distance. A larger air gap allows for an undisturbed air flow. Air has a higher thermal conductivity compared to wood. Since the TEC radiates cold air into the air gap, the air gap distance should be minimized to decrease the volume that the TEC must cool. This also reduces the temperature since the input power is constant and the amount of work is reduced. The current air gap is 20mm which provides enough space to add another 6mm sheet without compromising air flow. As a result, adding a sheet of wood on each face on the inside of the nest provides better performance.

5.3.4 Cable Management and Circuit Casing

The power circuitry and the microcontroller unit require housing and protection from the elements. The housing is in the form of an independent box which allows for the components to be accessed in the event of maintenance. The separate compartment built for the housing joint to the nest can be placed on top of the nest or below the nest. Signal dispersion improves with height therefore the range and connectivity strength improves if the box is placed on top. However, the circuit housing becomes the first point of contact for sun rays. The build-up of heat causes the electronics to overheat thereby compromising performance and lifespan. When the box is placed at the bottom of the nest, it receives the maximum moisture protection and is guarded from direct sunlight. Since the nest is at a height of 1.5m above the ground the signal can still disperse to acceptable ranges.

Cables which run from the power circuit up to the TEC and cooling fans require casing since the cables resemble snakes. Cables can run from the circuit housing through the wood via drill holes into the airgap and connect to the TEC from the inside of the nest. Plastic cable holders can be used to hide the small exposed cables.

5.4 Final Design

The final design can be seen in Appendix 1, A3.

Parameter	Choice	Rationale
TEC	TEC1 12703	Cheap, available locally and offers a good wattage compared to the other options. Only one device will be used as the power requirement is too high.
TEC configuration	2 heatsinks, cooling fan, cotton insulating pad and thermal paste	The cold side heat sink is used as a radiator since the TEC is not efficient in cooling spaces when compared to surface areas. Thermal paste is used to improve the heat transfer from the TEC to the heatsink. The cotton insulating pad is used to isolate the hot side and cold side. The cooling fan is required on the hot side to maintain safe operation of the TEC.
Vent	Whirling Vane	It is better suited for stationary applications and it captures moving air from every angle. Aquarium tubing is used to fit onto the nozzle and pass through the hole at the face of the vent into the nest box. Four vents will be used on top of the roof at each corner which allows for symmetric and even airflow.
Second Layer	Internally Installed	It decreases the air gap to a suitable amount for airflow and decreases the amount of air the TEC has to cool.
Thermal Insulation	EPDM	Offers better thermal insulation than fibreglass.
Wood Polymer Solution	Decided Against	Not possible to soak the wood without disassembling the next and rebuilding.
Water Proof	EPDM	Has the best waterproofing capabilities and is non-toxic.
Circuit Housing	Below nest in a tray box	Allow for adequate signal dispersion whilst receiving the best protection.

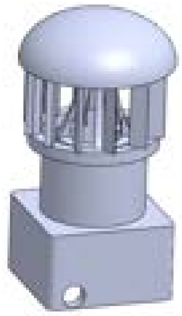
Table 5.8: Table showing the different wood types available

5.5 Testing

5.5.1 Acceptable Test Protocols

The following table presents the acceptable test protocols.

(a) Final Nest Design



(b) Vent Design

Figure 5.1: Final System Design

Label	**Description**	**URx:FRx**
ATP1	Given the existing nest design, additional features must be iteratively built on the old design without removing fundamental pieces of the nest	UR:FR1.
ATP2	Observe that the inside of the nest is made of wood, there are no crevices, the outside of the box is a dark colour and no cables are visible.	UR2:FR1; UR3:FR1
ATP3	Using a sound meter app, record the hum from the Peltier by placing the phone inside the box. Convert the scale from decibels to linear.	UR2:FR2
ATP4	Place a cup of water upside down onto the wood covered by EPDM and allow the water to soak. Measure the decrease in water level to determine the amount of water that has been absorbed.	UR3:FR1
ATP5	Measure, using a digital multimeter, that the current is 1.5A and the voltage is 6V. Observe that the TEC is switched on for 45 minutes every hour.	UR4:FR1
ATP6	Place the nest inside a box to be a test box, 1.5x bigger than the nest. Cut a hole in the top of the test box. Use a hairdryer to increase the temperature surrounding the nest. When the nest reaches at least 1.5 times the start value, turn the TEC on and measure the temperature change inside the next.	UR4:FR1
ATP7	Blow air into the rotors of the whirling vent and verify that air exits the tubing.	UR4:FR1
ATP8	Using an air pump, pump air into the vent entry and verify that the air is expelled upwards.	UR4:FR1
ATP9	Measure the thickness of the side panel and subtract 12mm (the thickness of the wood) to obtain the thickness of the damping membrane.	UR4:FR3
ATP10	Place a weight that is 1.5x the solar panel weight and observe the state of the wood after 10 hours.	UR5:FR1

ATP11	Treat the EPDM with vinegar for 8 hours. Afterwards, airdry the membrane for 24 hours to remove the chemical smell.	UR3

Table 5.9: Acceptable Test Protocols

5.5.2 Test Results

ATP1: The existing nest was built using a scaled-down model (down by 36%). The new features required vent holes and insertion points which were added before integrating the new pieces in.

Comment: Although the bird would have to be relocated while updating the nest, changes are able to be integrated without rebuilding the entire nest.

Judgement: Pass

ATP2: The nest is made entirely out of wood. The designed covers for electronics blend in with the nest.

Comment: The nest needs to be painted a dark colour before it can be used in practice.

Judgement: Pass

ATP3: The sound meter read 31db-A in the quiet room with the electronics off. Using a db-A index, 31db-A equates to a silent room. The Peltier and cooling fan were powered and the meter had no visible change.

Comment: When the cooling fan was obstructed the meter increased the reading by 2 db-A when measured outside the nest. A secondary measurement was taken with the meter inside the nest and there was no considerable change on the meter.

Judgement: Pass

ATP4, ATP9: Three tests were done, one with the damping membrane, one with fibreglass and one with no damp proofing. The following table presents the results. The waterproofing materials' thickness was measured with a ruler and recorded. **Comment:** EPDM provides the best waterproofing

Test	Drop (mm)	Volume Absorbed m^3
No Proofing	4	6.91×10^{-4}
EDPM	0	0
Fibreglass	2	3.455×10^{-4}

Table 5.10: Table showing the test results of water soakage

however sink holes are required to allow the water on the first sheet of the double sheeted wood to dry out.

Judgement: Pass

ATP5,6: A hairdryer was used as a heat source to simulate the Kalahari, modelled by a 600 x 400 x 400 cardboard board box. The box temperature increased to 47 degrees from an initial temperature of 21 degrees in 125 seconds. The TEC was switched on after sealing the test box whilst keeping the heat source on. The current was measured to be 1.7A and the voltage was 5.8V. The TEC module cooled the nest by 6 degrees using a 60x60 heatsink and by 9 degrees using a 100x120 heatsink (after 45 minutes). 2 more tests were done to improve the integrity of the results. The big heat sink resulted in an average of a 9-degree drop and the small heat sink resulted in an average of a 5-degree drop. The results were skewed due to the test box having sinkholes. The ventilation was not able to be tested during these conditions as a wind source removed the hot air from the test box.

Comment: In the next iteration of the test, a better test box must be constructed.

Judgement: Fail

ATP7: The air did not pass through the nozzle it was too narrow therefore air escaped back out of the turbine. The fins should be curved and wider with more fins per rotation to prevent the air from escaping.

Judgement: Fail

ATP8: High-velocity air exits the vent on the other side however slow-moving air could not travel up the vent and exit.

Comment: The vent can be angled downwards away from the nest which the air can exit.

Judgement: Fail

ATP9: A 12kg weight was placed on the 6 mm roof lid elevated 1m above the ground. The wood showed significant cracks after 1 hour. A second test was done on the 12mm lid with the same weight. There were no cracks after 10 hours.

Comment: The strength of the two-layer system increased since each face's thickness increased and increased the support thickness.

Judgement: Pass

5.6 Conclusion

The main objective of the ornithologist was to cool the nest to a maximum of 35°C, maximizing the passive cooling capability and preventing active cooling from disturbing the birds. The objective underwent significant tests and the results significantly verified that the design worked within the scope of the project. The Peltier system in this design partially achieved the specification at a low efficiency. The ventilation system worked in isolation and the turbine design failed however this will be addressed in the next iteration by adjusting the size of the rotor fins, the number of fins and the nozzle size in the vent. The system was able to cool the nest by varying degrees depending on the ambient conditions. In the worst case scenario, the design reduced the temperature by 9 degrees.

Chapter 6

Sensing LWSHOLOO1

6.1 Introduction

This chapter of the project details the design process of the sensing subsystem. This subsystem is responsible for triggering the cooling subsection and recording information for the front-end system. It begins by establishing a set of specifications, building on the user requirements set out by Ben. Furthermore, it outlines corresponding acceptance test procedures that are subsequently used to test the final subsystem. Following this, various hardware design choices will be discussed in alignment with user requirements and specifications, and once discussed a final implementation will be presented. This implementation will then be tested and the results will be compared to the acceptance test procedures.

6.2 Requirements and Specifications

This section details the requirements and specifications. In this case non-functional describes characteristics that contribute to the quality of the system.

6.2.1 Non-Functional

Requirements		Specifications		Acceptance Test	
SRE-1	Sensors must function in the Karoo.	SSP-1	Range: Temperature Sensors must operate and record values in the range: of 0 °C - 65°C.	SAC-1	Sensors must operate and record values in the range: of 0 °C - 65°C.
		SSP-2	Range: Humidity sensors must operate and record in the range of 10-60% RH.	SAC-2	Humidity sensors must operate and record in the range of 10-60% RH.
SRE-2	Measurements must be accurate.	SSP-3	Accuracy: Temperature sensor must have an accuracy of ± 0.5°C.	SAC-3	Temperature sensor must have an accuracy of ± 0.5°C.
		SSP-4	Accuracy : The humidity sensor must have an accuracy of ± 3% RH.	SAC-4	The humidity sensor must have an accuracy of ± 3% RH.
SRE-3	Measurements must be taken frequently.	SSP-5	Frequency: Temperature sensor must be able to take at least a reading per minute.	SAC-5	Temperature sensor must be able to take at least a reading per minute.
		SSP-6	Frequency The humidity sensor must be able to take a reading every 5 seconds.	SAC-6	The humidity sensor must be able to take a reading every 5 seconds.

Table 6.1: Non-functional Requirements, Specifications and Acceptance Tests Tractability matrix

6.2.2 Functional

Requirement		Related Specification		Acceptance Test	
SRE-4	Readings must be accessible from any device.	SSP-7	The sensor values must be stored in a text file and accessed by the front-end.	SAC-7	Sensor values must be correctly formatted appear in the texfile with no noticeable latency.
SRE-5	Automated cooling of the nest.	SSP-8	The system live processes the data and must send an output signal to trigger the cooling system when the nest is too hot.	SAC-8	The sensor submodule must turn a GPIO pin high when the TEC must be on and LOW when it must be off.

Table 6.2: Functional Requirements, Specifications and Acceptance Tests Tractability matrix

6.3 Hardware Selection

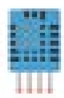
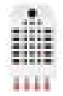
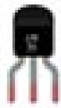
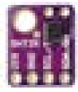
						
Sensor	**DHT11**	**DHT22**	**LM35**	**SHT3x**	**BME280**	**BMP180**
Measures	Temperature Humidity	Temperature Humidity	Temperature	Temperature Humidity	Temperature Humidity Pressure	Temperature Pressure
Supply Voltage	3 to 5.5V	3 to 6V	4 to 30 V	3.3 to 5.5V	3.3 to 5V	3.3 to 5V
Temperature Range	0 to 50ºC	-40 to 80ºC	-55 to 150ºC	-40 to 125ºC	-40 to 85ºC	0 to 65ºC
Accuracy Temperature	+/- 2ºC (at 0 to 50ºC)	+/- 0.5ºC (at -40 to 80ºC)	+/-0.5ºC (at 25ºC)	+/- 0.2ºC (at 0 to 65ºC)	+/-1ºC (at 25ºC)	+/-0.5ºC (at 25ºC)
Humidity Range	20-90% RH	0 to 100% RH	NA	0 to 100% RH	0-100%	NA
Accuracy Humidity	± 5% RH	± 2% RH	NA	± 2% RH	+-3%	NA
Dimensions	15.5mm x 12mm	40mm x 23mm	6mm x 20mm	12mm x 10 mm	15mm x 10 mm	21mm x 18mm
Seconds Per Sample	1 second	2 seconds	Bounded by ADC	0.5 seconds	1 second	1/128 seconds
Support (Arduino Ide)	Adafruit DHT Library Adafruit Unified Sensor Library	Adafruit DHT Library Adafruit Unified Sensor Library	analogRead()	Adafruit SHT31 library Adafruit Unified Sensor Library	Adafruit BME280 library Adafruit Unified Sensor Library	Adafruit BMP085 Adafruit Unified Sensor Library
Price	R33.91 Communica	R68.70 Communica	R24.90 Pi Shop	R75.65 Communica	R69.90 Pi Shop	R122.90 Mantech Electronics

Table 6.3: Comparison of popular temperature sensors

Information gathered from: DHT11 [47][48] DHT22[47][49] LM35[47][50] SHT3x[51] BME280[47][52] BMP180[47][53]

Table 6.3 summarizes six options capable of fulfilling the fundamental functionality requirements of the required temperature sensor and capable of successfully integrating with any of the MCU options. It is therefore important to choose a sensor based on the non-functional requirements as it will ensure the quality of the overall system. Firstly, under specification SSP-1 the temperature sensors are required to operate in the range of 0 °C - 65°C, all the temperature sensors meet this requirement. Secondly, under SSP-3 the temperature sensors are required to have an accuracy of +/-0.5ºC, the DHT11 and BME280 both do not meet this requirement and are therefore disqualified. Thirdly, from specification SSP-5 the temperature sensors are required to take a reading every minute, all temperature sensors meet this requirement. Therefore, the DHT22, LM35, SHT3x and BMP180 satisfy all the temperature specifications making them viable options. However, the DHT22 and SHT3x stand out as due to their additional capability of measuring humidity. This would negate the need to have separate sensors and would simplify the data-logging process. Both of these sensors meet SSP-2 (humidity range), SSP-4 (humidity accuracy) and SSP-6 (frequency of humidity readings). Although it is not strictly necessary, the SHT3x offers a superior temperature operating range and better temperature accuracy. Given their similar pricing and availability, the SHT3x is chosen as the preferred hardware choice.

6.4 Implementation

The sensor implementation is very straightforward. It was connected to the ESP8266 as depicted in Figure 6.1. It operates by taking a temperature and humidity reading and writing it to the textile along with the current *linecountFile* value. Subsequently, it increments the index value. If the read-in value exceeds the pre-set ideal maximum temperature, it sets the D6 pin too high to trigger the TEC to turn on. If this value is within the acceptable range, it sets the D6 pin low.

```
digitalWrite(D6, LOW); // Set D6 pin to LOW
```

It is important to note that the linecountFile value is used by the getGraphData() function so that it knows how many total values there are, which is used in calculating the range of values that must be displayed. This is further detailed in section 7.5.3.

6.5 Results and Testing

During development and testing, debugging statements were printed to the serial monitor to verify program execution. These results were then cross-referenced with the values written in the text file to confirm correct functionality. Figure 6.2 shows the output from the sensor after it was blown on to check that it successfully measured an increase in temperature and humidity readings. In this experiment, the ideal temperature of the nest was set to 25°C. The serial monitor results are displayed in Figure 6.2. When comparing Figure 6.2 and Figure 6.3 it is clear the readings are correctly recorded in the text file. Furthermore, the toggling of the D6 pin was tested with a voltmeter, confirming that it was triggering the GPIO pin at appropriate times.

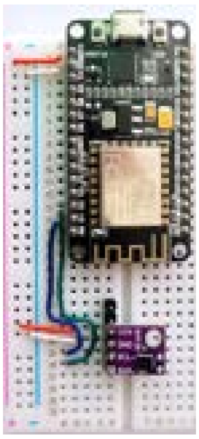


Figure 6.1: Circuit connecting the sensor to the ESP8266

```
Nest is too hot, TEC ON
Writing to file:4977,25.82,93.6
Nest is too hot, TEC ON
Writing to file:4978,24.97,92.9
Nest is cool, TEC OFF
Writing to file:4979,24.00,88.2
Nest is cool, TEC OFF
Writing to file:4980,23.80,84.0
Nest is cool, TEC OFF
Writing to file:4981,25.42,83.5
Nest is too hot, TEC ON
Writing to file:4982,25.31,86.4
Nest is too hot, TEC ON
Writing to file:4983,24.97,88.5
Nest is cool, TEC OFF
Writing to file:4984,24.44,90.4
Nest is cool, TEC OFF
```

Figure 6.2: Serial Monitor output when the sensor was blown on

```
4972,28.59,92.3
4973,28.43,92.8
4974,28.31,93.2
4975,27.97,93.4
4976,27.08,93.5
4977,25.82,93.6
4978,24.97,92.9
4979,24.00,88.2
4980,23.80,84.0
4981,25.42,83.5
4982,25.31,86.4
4983,24.97,88.5
4984,24.44,90.4
4985,24.30,87.6
4986,24.21,82.4
4987,24.16,78.1
4988,24.07,74.6
4989,24.03,72.4
```

Figure 6.3: New readings correctly written to file

6.6 Analysis of acceptance tests

This section analyses the sub-subsystem to ensure that it meets the non-functional and functional specifications.

6.6.1 Non Functional

Requirements		**Specifications**		**Acceptance Test**	
SRE-1	Sensors must function in the Karoo.	SSP-1	Range: Temperature Sensors must operate and record values in the range: of 0 °C - 65°C.	SAC-1	Sensors must operate and record values in the range: of 0 °C - 65°C.
		SSP-2	Range: Humidity sensors must operate and record in the range of 10-60% RH.	SAC-2	Humidity sensors must operate and record in the range of 10-60% RH.
SRE-2	Measurements must be accurate.	SSP-3	Accuracy: Temperature sensor must have an accuracy of ± 0.5°C.	SAC-3	Temperature sensor must have an accuracy of ± 0.5°C.
		SSP-4	Accuracy : The humidity sensor must have an accuracy of ± 3% RH.	SAC-4	The humidity sensor must have an accuracy of ± 3% RH.
SRE-3	Measurements must be taken frequently.	SSP-5	Frequency: Temperature sensor must be able to take at least a reading per minute.	SAC-5	Temperature sensor must be able to take at least a reading per minute.
		SSP-6	Frequency The humidity sensor must be able to take a reading every 5 seconds.	SAC-6	The humidity sensor must be able to take a reading every 5 seconds.

Table 6.4: Analysis of Non-Functional Acceptance Tests

6.6.2 Functional

Acceptance Test		**Acceptance Test Result**
SAC-1	Sensors must operate and record values in the range: of 0 °C - 65°C.	**PASSED**: chosen sensor operates and records in the range 40 ºC to 125ºC.
SAC-2	Humidity sensors must operate and record in the range of 10-60% RH.	**PASSED**: chosen sensor operates and records in the range 0% to 100% RH.
SAC-3	Temperature sensor must have an accuracy of ± 0.5°C.	**PASSED:** Chosen sensor has an accuaricy of ± 0.2ºC .
SAC-4	The humidity sensor must have an accuracy of ± 3% RH.	**PASSED:** Chosen sensor has an accuaricy of ± 2%RH.
SAC-5	Temperature sensor must be able to take at least a reading per minute.	**PASSED:** chosen sensor can record a value every 0.5 seconds.
SAC-6	The humidity sensor must be able to take a reading every 5 seconds.	**PASSED:** chosen sensor can record a value every 0.5 seconds.

Table 6.5: Analysis of Functional Acceptance Tests

6.7 Summary

The chosen hardware, an SHT3x sensor, fulfils all the functional requirements and non-functional requirements. The implementation ensures the sensor data is written to the text file for later analysis by the front-end subsystem. Testing has confirmed the subsystem functions as intended, triggering the cooling system when the temperature exceeds a predefined threshold and recording the values correctly.

Chapter 7

Front End LWSHOL001

7.1 Introduction

This chapter of the project details the design process of the front-end subsystem. This subsystem is responsible for providing an interface for the user to access the temperate and humidity readings. It begins by establishing a set of specifications, building on the user requirements set out by Ben. Furthermore, it outlines corresponding acceptance test procedures that are subsequently used to test the final subsystem. Following this, various hardware design choices will be discussed in alignment with user requirements and specifications, and once discussed a final implementation will be presented. This implementation will then be tested and the results will be compared to the acceptance test procedures to ensure they were met.

7.2 Requirements, Specifications and Acceptance Tests

7.2.1 Non-functional

In this report, non-functional refers to characteristics that improve the quality of the subsystem but do not affect the overall functionality.

User Requirements		Related Specification		Acceptance Test	
FERE-1	The front end is easy to use.	FESP-1	Styling: The system must use styling to improve appearance of the system. The system must have clear and consistent stylistic choices .	FEAC-1	The system has less than 10 buttons. The system must use less than 5 colors. The system must use 1 font family.
			Usability: the system must have a clear call to action and clear sectioning. The system must be interactive.	FEAC-2	The system must have clear sectioning. The system must have clear headings. The system must respond to user input.
		FESP-2	Responsiveness: The system must function and display correctly on a range of screen sizes and devices.	FEAC-3	The system must automatically adjust to different screen sizes without compromising the layout and clarity. The system must be compatible with iPhones, Android phones and laptops.
FERE-2	There must be no recurring costs.	FESP-3	Cost: The system must not require any licensing or recurring fees.	FEAC-4	The total budget for the software must not exceed R0.

Table 7.1: Non-functional Specifications, Requirements and Acceptance Test Tractability matrix

7.2.2 Functional

User Requirement		Related Specification		Acceptance Test	
FRRE-3	Access Data From Phone at the bottom of the nest.	FESP-4	Transmission: The system must wirelessly transmit the information.	FEAC-5	The user must be able to access the data wirelessly in under a minute.
		FESP-5	Transmission: The user must be able to download content to their device from the system.	FEAC-6	The graphs (PDF) and raw data must be downloaded onto the user's phone on request.
		FESP-6	Security: The system must authenticate devices before transmitting information.	FEAC-7	The system must authenticate users before transmitting the data.
		FESP-7	Data: The System must analyse data from a textfile .	FEAC-8	The system must read from a textfile when creating graphs and statistics.
FRRE-4	Data must be presented visually	FESP-8	Data: Temperature and humidity data must be displayed on 2 separate graphs. Graphs can display variable amounts of data based on user input.	FEAC-9	The data from the textfile must be displayed as graphs with varying time ranges.

Table 7.2: Functional Specifications, Requirements, and Acceptance Test Tractability matrix

7.3 Wireless Communication Design Choices

There are various wireless communication protocols available including Wi-Fi, Bluetooth, Bluetooth low energy, ZigBee and RF. All of these protocols would be able to meet specification FESP-4 (the subsystem must wirelessly transmit the information) and specification FESP-6 (the user must be able to download content to their device from the subsystem). However, to meet specification FESP-7 (data must be displayed visually) a lot of these options will encounter difficulties. It is possible to create and send a PDF containing graphs to the user however this would greatly limit the functionality and design of the subsystem. Wi-Fi therefore stands out as the best choice as it would be able to host a password-protected network that will allow the user access to a website. This website opens up the possibility of user interaction and input as well as a clear, simple and intuitive interface. Therefore, Wi-Fi is the chosen wireless communication protocol.

7.4 Hardware Selecting

This section details the design choices made for the front-end subsystem. This is achieved by first comparing popular hardware choices, which are then analysed in order to choose the best Micro Controller.

The ESP8266, the ESP32 and the Raspberry Pi 0 are all able to host a website wirelessly and therefore will meet be able to meet FESP4-FESP8 if utilized correctly. Furthermore, they all have a large enough working temperature range to successfully function in the Karoo. Of the displayed options the Raspberry Pi is the most powerful, offering superior flash storage and processing capabilities[54]. However, this results in higher power consumption. The ESPs both offer sleep mode which can be an effective way of conserving power. As a bonus, they are both significantly cheaper than the Raspberry Pi. Although the development board option of the ESP8266 is more expensive and would be needed for the development of the system, the final system would only require the ESP8266 module itself. This puts the price of the ESP8266 down significantly. Furthermore, the ESP8266 consumes significantly less power than the ESP32 and Raspberry Pi. The one potential downside of the ESP8266 is its minimal flash, however, this can be easily and cheaply addressed with a small SD card and an SD card reader. Therefore, the ESP8266 is the best option and will be used to develop the front-end subsystem.

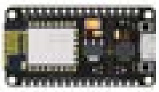
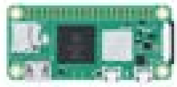
Descriptor	**ESP8266**	**ESP32**	**Raspberry Pi 0**
Component:			
Mcu	Single-core	Dual-Core	Single-core CPU
Wi-Fi Module	✓	✓	✓
Bluetooth	X	✓	✓
Power Requirements	70mA	160~260mA	120 mA
Flash (Expandable With SD Card)	16MB	32MB	2MB
Gpio	17	34	40
Power Supply	3.3V	5V	5V
Spi/I2c/I2s/Uart	1/1/1/2	4/2/2/2	3/2/2/2
Adc	10-bit	12-bit	17-bit
Working Temperature	-40ºC to 85ºC	-40ºC to 125ºC	0°C and 85°C
Size	58 mm x 29 mm	51.4mm x 25.4mm	65mm x 30mm
Module Price	R86.65	R120.87	R309
Dev Board Price	R200	R159	R309

Table 7.3: Front-End Hardware Choice comparison

Information gathered from ESP8266 [55], RaspberryPi0 [56], ESP32 [57].

7.5 Implementation

7.5.1 Hosting a web server

ESP8266 can host two different types of servers:

1. Asynchronous - tasks can be executed concurrently without blocking each other.
2. Synchronous - tasks are executed in a sequence

To handle multiple connections and respond simultaneously an asynchronous web server chosen and implemented on the ESP.

The code below creates the server and sets the network credentials that offer security to the website and aligns with FESP-6, the system must authenticate devices before transmitting information.

```
const char *ssid = "NestAware";
const char *password = "NestAware";
AsyncWebServer server(80);
void setup() {
    Serial.begin(115200);
    WiFi.softAP(ssid, password);
```

```
    server.begin();}
void loop() {}
```

7.5.2 Designing the Website using Bootstrap (HTML)

The website's design and functionality is a crucial part of the system as an effective and well-communicated website improves the overall usability of the entire system. Since this project is a potential replacement for the current iButton implementation it is imperative that the website feels professional and finished. In alignment with FESP-1, styling and usability, the website was created with a consistent colour pallet and fonts. Figure ?? shows the style choices of the website.

Figure 7.1: Logo, fonts and colors utilized in the website

To ensure the styling and format were consistent and aesthetically pleasing, the HTML and CSS styling were designed and generated using Bootstrap Studio. However, this created slight problems as trying to combine the style sheets and HTML into the ESP code made the code hard to read and very difficult to edit. I therefore decided to use SPIFFS file system that 'served' the files when and where they were needed. This improved the modularity of the code as the style sheets, Javascript and HTML could easily be updated and regenerated independently of the ESP code. Below is a code snippet that shows an example of the SPIFF file system serving a style sheet.

```
server.on("/assets/bootstrap/css/bootstrap.min.css", HTTP_GET, []
(AsyncWebServerRequest * request) {
request->send(SPIFFS, "/bootstrap.min.css", "text/css");
});
```

It must be noted that any Arduino IDE version above 2.3.2 did not support the use of SPIFFS however this was easily solved by downloading the legacy IDE.

7.5.3 Retrieving Data

To keep the design process as modular as possible, this part of the code was initially designed with fake data to ensure that it could be developed and tested independently of the sensing subsystem. Furthermore, to maximise the use cases of this code, the function that reads the text file is all done in terms of the number of days and time between readings, this means that the code will still work if the project is extended to show a year of values or if the logging rate was updated. Furthermore, the code not only generates the values to plot but also generates important statistics like temperature range, time in the ideal range and number of readings. The flowchart in Figure ?? shows the simplified functionality of the algorithm. The algorithm works by having a target number of days to find data for. It first calculates the number of readings that will be required. It then calculates the starting position of this data, if startingIndex is calculated as negative, it means there are not enough readings in the text file and it therefore starts at index 0. For the graphs to be as readable as possible, a maximum

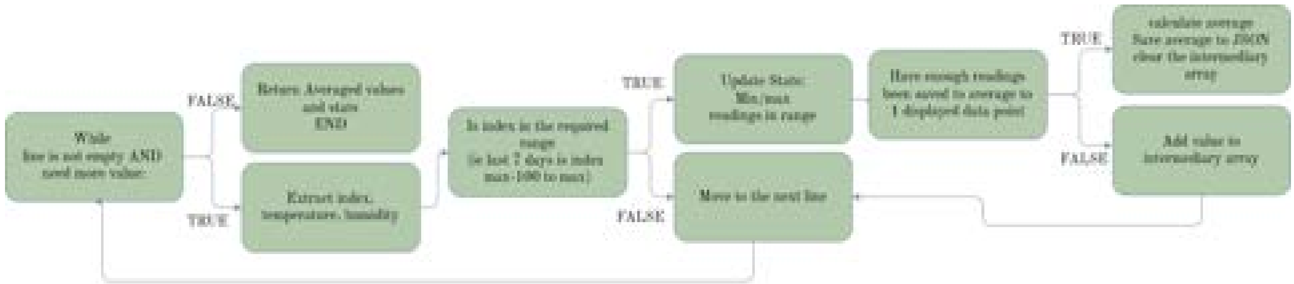


Figure 7.2: Flow-diagram showing the algorithm of getGraphData()

of 40-60 readings were shown. The program then averages sections of readings into 1 of the 40-60 displayed readings and returns these values as a JSON.

7.5.4 Designing and Integrating graphs

There are various ways to create graphs on a website however in order to keep with the style of the website as well as utilise existing functionality, I used the JSGraphs library. To integrate the graphs, a canvas was created in the HTML where the graphs are required.

```
<div class="card-body" style="height:100%;max-height:400px">
<canvas id="tempChart" style="width:100%;max-width:600px"></canvas>
</div>
```

On a button click, the ESP code reads through the file and generates the values that JSGraph must plot, it then calls the graph function which generates the maximum and minimum temperatures that were recorded over the selected time period. Below shows the function that calls the getGraphData with the input parameters 30- number of days and 60- number of points to display.

```
server.on("/api/getGraphData30", HTTP_POST, [](AsyncWebServerRequest * request) {
  Serial.println(request->params());
  String json = getGraphData(30,60 );
  request->send(200, "application/json", json); });
```

This function is called when the user clicks on the 30 Days button. This action will update the temperature graph, humidity graph, temperature stats, and humidity stats. Below is the event listener for the 30 Days button:

```
Button30Days.addEventListener("click", getGraphData30);
```

7.5.5 Downloading data

Finally, the user is able to download the text file of raw data, this is achieved through the following code which is triggered with an event listener:

```
server.on("/SensorData.txt", HTTP_GET, [](AsyncWebServerRequest * request) {
  Serial.println("Downloading File");
  request->send(SPIFFS, "/SensorData.txt"); });
```

The user is also able to download the graphs as a PDF by using the built-in window.print() function

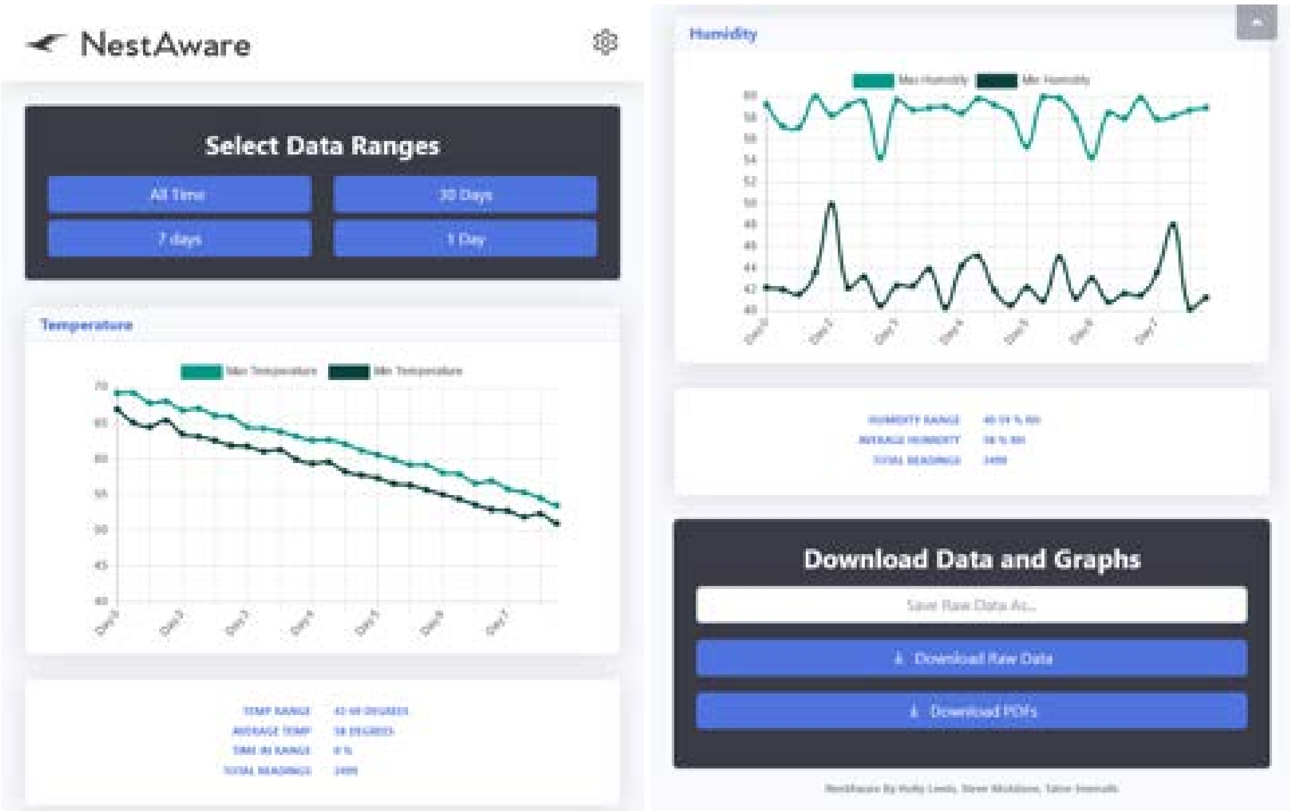


Figure 7.4: Screenshot of a website showing temperature and humidity graphs and statistics for 7 days

```
document.getElementById('ButtonPDFDownload').addEventListener('click', () => { window.print();});
```

7.6 Testing Results

This section details the evaluation of the final front-end subsystem. Each section of the subsystem is tested and compared to the initial acceptance test procedure.

7.6.1 Hosing web server and website

The ESP8266 successfully hosted a password-protected Wi-Fi network that could be accessed on any device that is in range.

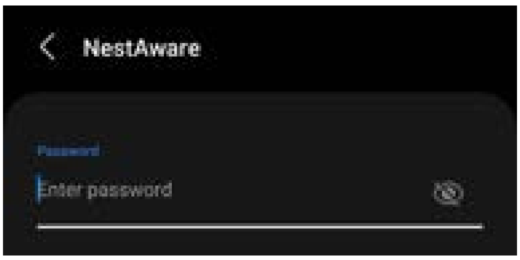


Figure 7.3: Screenshot of WIFI network hosted by ESP

Once the user enters the password and goes to the correct URL the website is successfully displayed. The website fits any screen size without compromising the content and layout. Furthermore, the style is clear and consistent. This can be seen in Figure 7.4.

7.6.2 Correct Display of data

To test the graphs, fake data was created using a Python script. This fake data had predefined maximums and minimums that could then be verified when reading off the graph and the range statistic. Furthermore, this

Figure 7.5: Screenshot showing the website responding to different screen sizes.

Figure 7.6: Screenshot showing the website responding to variable time range request

was cross-referenced using Microsoft Excel to calculate the statistics. The fake data used intentionally has a large range and a big jump to make sure the axes are still readable with erratic data. Each of the 4 range options were then tested to make sure they were displaying the correct data.

7.6.3 Correct Download of data

Following this, the download functionality was tested to ensure that the user is receiving the correct raw data and PDFs.

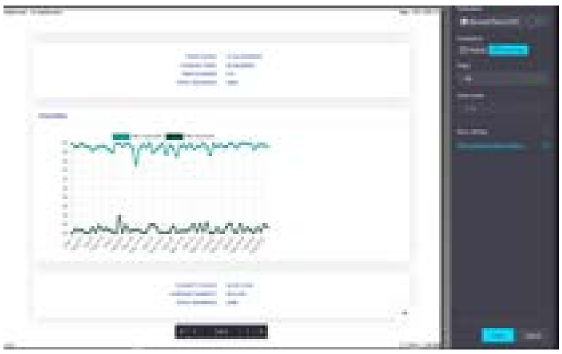


Figure 7.7: Screenshot of download PDF option

Figure 7.8: Screenshot showing the download text file option

To ensure the textile that was downloaded contained the correct data, a fake text file was uploaded to the ESP8266 using the SPIFFs file system, this was then downloaded through the website and compared with the original, the results in Figure **??** showed that the text file was being saved and downloaded correctly

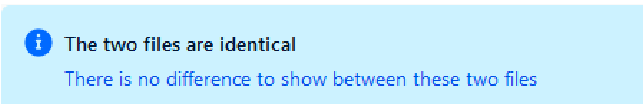


Figure 7.9: Comparing the uploaded and downloaded text files to verify functionality

7.7 Acceptance Test Analysis

This section details the acceptance test analysis, that determines if the subsystem has met all the necessary requirements.

7.7.1 Non-Functional

Acceptance Test		Acceptance Test Result
FEAC-5	The user must be able to access the data wirelessly in under a minute.	**PASSED**: As seen in *Figure 6.3* the user can easily connect to the wifi network, and then enter the URL into their browser of choice. This process is familiar to all users and therefore takes approximately 40 seconds for a first-time user and approximately 20 seconds for an experienced user.
FEAC-6	The graphs (PDF) and raw data must be downloaded onto the user's phone on request.	**PASSED**: The user can download the graphs and raw file when clicking the download button (*Figure 6.4*) the files are then downloaded to the user's device as seen in *Figure 6.7* and *Figure 6.8*.
FEAC-7	The system must authenticate users before transmitting the data.	**PASSED**: The user must enter a password to connect to the WIFI network as seen in *Figure 6.3*. The website is only accessible once the user is accepted onto the wifi network.
FEAC-8	The system must read from a textfile when creating graphs and statistics.	**PASSED**: The system creates graphs and statistics that correspond to the text file as seen in *Figure 6.3*, and *Figure 6.5*.
FEAC-9	The data from the textfile must be displayed as graphs with varying time ranges.	**PASSED**: The system creates graphs and statistics over varying time ranges (1 day, 7 days, 30 days, all time) as seen in *Figure 6.3*, and *Figure 6.5*.

Table 7.4: Analysis of Functional Acceptance Tests

7.7.2 Functional

Acceptance Test		Acceptance Test Result
FEAC-1	The system has less than 10 buttons. The system must use less than 5 colors. The system must use 1 font family.	**Passed:** The system styling is clear and readable and utilizes 4 colours *Figure 6.1,6.4)* There are 7 options for the user to click/input data.
FEAC-2	The system must have clear sectioning. The system must have clear headings. The system must respond to user input.	**Passed:** The website uses labelled cards to separate sections. The system correctly responds to the user clicking the button as seen in *Figure 6.6*.
FEAC-3	The system must automatically adjust to different screen sizes without compromising the layout and clarity. The system must be compatible with iPhones, Android phones and laptops.	**Passed:** the system responds to changing screen size as seen in *Figure 6.5*. The system is accessible on any device (tested on a phone, laptop, or tablet).
FEAC-4	The total budget for the software must not exceed R0.	**Passed:** The total cost for the software is R0.

Table 7.5: Analysis of Functional Acceptance Tests

7.8 Summary

The front-end design successfully meets all the functional and non-functional requirements. The ESP8266 effectively hosts a password-protected Wi-Fi network, allowing users to access a well-designed and responsive website displaying temperature and humidity data through graphs and statistics. Additionally, users can download raw data as a CSV file or generate a PDF report of the graphs.

Chapter 8

Conclusions

The purpose of this project was to develop a thermal management and monitoring system for use in Yellow-Billed Hornbills nests. This report began with an introduction and an further refinement of the problem,into the problem. Next chapter 3 contains an exploration of Thermal Regulation Systems, power solutions, sensor data capturing and existing transmission techniques in the form of a literature review.

Thereafter, chapter 3 explains the development, design and testing of the power supply unit (PSU). The PSU met all the prescribed Acceptance Test Procedures. However, the evaluation of ATP1 could not be concluded as the parts could not be printed in time. To improve the PSU design, incorporating a MOSFET driver for amplifying the 3.6V output from the microcontroller unit to drive the MOSFET gate is recommended. Additionally, integrating an optocoupler to isolate the high-voltage side from the low 3.6V MCU output can protect against over-voltage incidents. These modifications offer potential enhancements to the PSU's functionality and safety, aligning it more closely with operational requirements. Further refinement and experimentation by these suggestions can optimize the PSU's performance and reliability.

Following this, chapter 4 contains the development, design and testing of the thermal regulation system and the physical enclosure. The primary objective of the cooling system was to reduce the internal temperature to a maximum of 35°C. The system utilized active and passive cooling methods. Extensive testing and evaluations were conducted to assess the performance of the proposed design within the project's scope. A damping membrane provided an increase in thermal insulation and the vents allowed air flow to expel hot air. While the ventilation system functioned in isolation, the designed turbine proved ineffective, necessitating modifications to the rotor fin size, fin count, and nozzle sizing in future iterations. The Peltier thermoelectric cooling system partially achieved the specified temperature requirements with low efficiency. The overall system demonstrated varying degrees of cooling success depending on ambient environmental conditions. By addressing the shortcomings in the updated design, the cooling performance can be enhanced to boost the chances of the Southern Yellow-billed Hornbills.

Subsequently, chapter 5 describes the development, design and testing for the sensing subsystem. The sensing subsystem successfully achieved its aim of recording temperature and humidity values for use by the front end. Furthermore, it successfully triggered the thermal regulation system. Were the project to be extended, integrating a clock module would be highly beneficial, this would mean that instead of an index value, there would be a time stamp.

Lastly, chapter 6 explores the development, design and testing of the front-end system. The ESP8266 effectively hosts a password-protected Wi-Fi network, allowing users to access a well-designed and responsive website displaying temperature and humidity data through graphs and statistics. Additionally, users can download the raw data as a text file or generate a PDF report of the graphs. To improve the front end, high-urgency alerts could be incorporated. This would entail sending out SMSs or emails to alert the researchers if the nest reaches a critical temperature .

In summary, the project achieved the goals that were set out, by successfully designing and testing a thermal management and monitoring system specifically for the Yellow-Billed Hornbill's nests.

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Appendix A

Git Repository

Git Hub Repository

Appendix B

Mechanical Thermal System(Appendix 1)

B.1 Air Scoop Vent

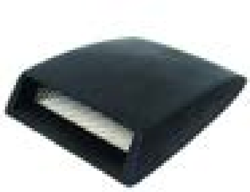


Figure B.1: Air Intake Scoop Vent

B.2 Whirling Vane Vent

Figure B.2: Whirling Vane Vent

B.3 Final Designs

Figure B.3: Built Nest Box

Appendix C

Power Subsystem - MHLSTE012

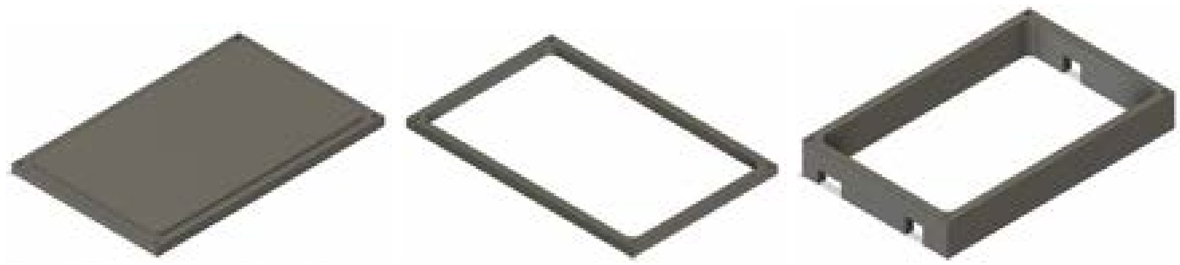
C.1 Buck Converter Results

(a) Signal Generator PWM

(b) Input Voltage (12V) and Output Result

Figure C.1: Buck Converter Measured Results

C.2 Power Supply Enclosure



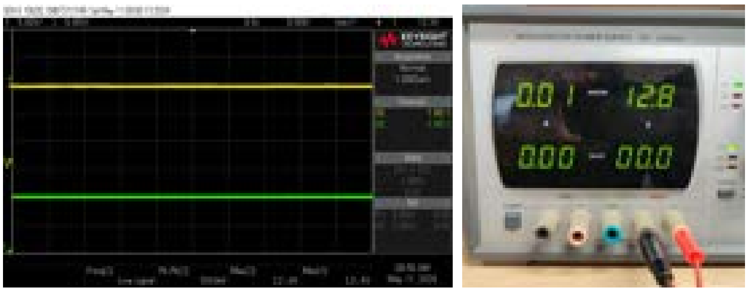
(a) Top Cover

(b) Mount To Battery

(c) Side Cover With Port Cutouts

Figure C.2: Weather Proofing Parts

C.3 Charger Results



(a) DC Input & Output from Charging Circuit

(b) Charger Current Drawn Circuit

Figure C.3: Charger Circuit Measured Results

Appendix D

Bill of Materials

ITEM NAME	NUMBER	PRICE PER UNIT	TOTAL PRICE
POWER SUBSECTION			
7.2Ah battery	1	230	230
LM317T Voltage Regulator	2	9.19	18.38
300mm by 110 mmVeroboard	1	90	90
1N5408 Diode	1	1.55	1.55
IRF740 MOSFET	1	26.37	26.37
IRFZ44N MOSFET	2	8	16
78uH Inductor & 4.7uF Capacitor	1	57.23	57.23
USB A port	1	6.61	6.61
Block Screw Block terminals	4	3.39	13.56
Resisors(62Ohm, 330 Ohm, 15kOhm, 1.5kOhm)	1	0	0
Resisors(1kOhm, 2.2kOhm, 4.7kOhm, 7.2kOhm)	1	0	0
Resistor (10kOhm) & Potentiometer	1	0	0
TL431 Shunt Regulator	1	37.04	37.04
Solar Panel	1	500	500
TOTAL POWER			996.74
COOLING SUBSECTION			
TEC1 12706	1	85	85
Cotton Washer Insulation	1	10.01	10.01
Low Current Fan	1	51.56	51.56
Heat Sink Large	1	91	91
Heat Sink Small	1	15.34	15.34
Wood	0.2	341	68.2
TOTAL COOLING			321.11

ITEM NAME	NUMBER	PRICE PER UNIT	TOTAL PRICE
SENSING SUBSECTION			
SHT3x	1	75.65	75.65
TOTAL SENSING			75.65
FRONT END SUBSECTION			
ESP8266	1	200	200
TOTAL FRONT END			200
OVERALL TOTAL			1593.5

Appendix E

Graduate Attributes Tables

E.1 MHLSTE012 GA Table

Power submodule MHLSTE012	**Where met**
GA 3: Engineering Design	Section 4.3, page(s) 14-19
GA 7: Sustainability and Impact of Engineering Activity	D-school (Appendix), Subsection(s) 4.3.4, page(s) 18 , Appendix E.1.1
GA 8: Individual, Team and Multi-disciplinary Working	Teams meetings and chats, final report and literature review, chapter 4, section 4.3.5
GA 10: Engineering Professionalism	All submission activities met including final report and presentation.

E.1.1 GA 7 - Sustainability and Impact of Engineering

The power submodule requirements encompass the vital design requirement for the PSU to be reliable, necessitating measures such as circuit protection against overcurrent, overcharge, and environmental elements. These design choices are to bring about a sustainable design, mitigating the harmful consequences of inadequate design practices on electronic component longevity and environmental impacts.

E.2 SWNTAL001 GA Table

Cooling Submodule SWNTAL001	**Where met**
GA 3: Engineering Design	Section 5.3/5.4, page(s) 28-34
GA 7: Sustainability and Impact of Engineering Activity	D-school, Subsection(s) 5.3, page(s) 28-31
GA 8: Individual, Team and Multi-disciplinary Working	Teams meetings and chats
GA 10: Engineering Professionalism	All submission activities met including final report and presentation.

E.3 LWSHOL001 GA Table

Sensing & Front-End Submodule	**Where met**
GA 3: Engineering Design	Section 6.3-6.4,7.3-7.5 page(s) 35-36, 39-42
GA 7: Sustainability and Impact of Engineering Activity	D-school, Subsection(s)6.1-6.2, 7.1-7.2, page(s) 34,38-39 ,
GA 8: Individual, Team and Multi-disciplinary Working	Teams meetings and chats, final report and literature review, chapter 4, section 4.3.5
GA 10: Engineering Professionalism	All submission activities met including final report and presentation.