EEE4113F Engineering System Design
Fork-tailed Drongo Camera Trap System

Group 7

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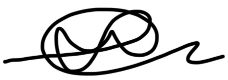

12 May, 2024

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Date

Contents

List of Figures

Chapter 1

Introduction

1.1 Background

The Fitzpatrick Institute of African Ornithology, based at the University of Cape Town, is a South African institution dedicated to biological research and conservation. With a primary focus on avian species, the Institute is at the forefront of efforts to study and preserve bird populations across the continent. One of its ornithologists, Ben Murphy, is currently researching the Fork-tailed Drongo in the Kalahari Desert.

Recent studies have indicated fluctuations in the populations of fork-tailed drongos in various desert regions. Despite the bird's black body, the fork-tailed drongo continues to exhibit successful breeding outcomes. This observation is important because other bird species are experiencing difficulties due to overheating, especially in their nests during the breeding season. Studying the fork-tailed drongo could provide insights into the behavior that facilitates its survival. This information can then be implemented to support other endangered species. However, the current methods used by ornithologists to monitor the Fork-tailed Drongos are inefficient. The reliance on cameras that require frequent maintenance and replacement leads to time spent on managing equipment rather than analyzing bird data. Additionally, the process of retrieving data from these cameras is both slow and inefficient. Large volumes of data must be collected in person without any automation, complicating data management and analysis. Moreover, the system often fails to operate during critical observation periods leading to a loss of data. By introducing a new, well-designed camera trap system, ornithologists will gain an advantage in better understanding and studying the birds.

1.2 Problem Statement

Ben, a PhD ornithology student researching the Fork-tailed Drongo in the Kalahari, needs a simple, cost-effective way to monitor the activity of the black-bodied birds at night, because existing monitoring methods are time-consuming and do not provide instant, accurate data about the bird.

1.3 Scope and Limitations

The scope of this project focuses on designing and implementing a highly efficient camera trap system for ornithologists studying the Fork-tailed Drongos. The goal is to provide ornithologists with a reliable, and easy-to-use tool that improves their research process. To achieve this, the project is divided into four sub-systems: namely power, sensing, user interface, and hardware. A solution for each subsystem will be identified and integrated into one final solution. The project is limited by:

- **Budget Limitation:** Allocated budget of R2000, requiring careful resource allocation.
- **Component Selection Constraints:** Limited to specific suppliers, which may affect the availability and variety of components.
- **Component Delivery Delays:** Potential delays in component delivery could impact the project timeline.
- **Observation Restrictions:** Inability to directly observe bird behavior in its natural environment, limiting understanding of interactions with the engineering systems.
- **Testing Limitations:** Constraints in testing the solutions in the Kalahari, where the fork-tailed drongos are located. The environment must be simulated.

1.4 Report Outline

This report details the full design process of a camera trap monitoring system.

Chapter 2, Problem Analysis, summarises the Design-School activities that aided in developing a solution. It contains design approaches that were weighed up and a final description of the problem and subsystems.

Chapter 3 presents a literature review, offering a comprehensive view of the problem. It includes detailed discussions on key topics such as the Kalahari ecosystem, the Fork-tailed Drongo, infrared technology, camera traps, and the deployment of engineering systems in remote environments.

Chapters 4 through 7 detail the design, testing, and implementation of each subsystem. User requirements for each module are derived from the initial problem statement, followed by a thorough design process. Specific test procedures are developed for each requirement, with a section discussing the results of these tests.

Chapter 8 concludes the report, summarizing all relevant details and offering recommendations for future iterations of the system.

The appendix contains additional resources and the GA requirements analyses for each team member. It also features the Bill of Materials (BOM), which lists all components used to develop the prototype along with the total cost of the system, providing a clear financial overview of the project resources. The appendix also includes a link to the project's Github repository.

Chapter 2

Literature Review

2.1 Introduction

Using camera systems to monitor and collect data on avian nesting behaviour is a crucial aspect of research in ornithology. Accurate nighttime footage of birds provides valuable insight into their activity, particularly the birds' relationship with their offspring. Obtaining this data in a cost effective, simple manner and storing it in an accessible digital storage system aids in understanding their nesting habits and behavioural patterns.

In this literature review, we will explore existing issues with deploying engineering systems in wildlife areas, focusing on the sustainability and longevity of the technology used in savanna biomes. We will further review the integration of electronic and hardware components into avian environments, which has become a growing research area in recent years. The impacts of such interventions on the birds' behaviour is further investigated through synthesizing existing research to better understand the implications of placing man-made components into the natural avian environment. We will further review traditional and modern techniques on how avian ecology has and is being monitored. The camera trap technique, coupled with infrared cameras, is then emphasized because of its supreme popularity in wildlife and avian monitoring systems. A final section on literature focused on data storage and power systems is, thereafter, included, to provide insight into the additional components of a plausible solution.

2.2 Holistic View of Environment and Species

The Fitzpatrick Institute is synonymous with deploying compact engineering systems in wildlife biomes to monitor bird behaviour. The location of the bird species being studied, particularly the Kalahari, often presents various obstacles for ornithologists. Firstly, the harsh environmental conditions, including high temperatures, sandstorms, and limited water sources, can all pose challenges for the operation. The vast and remote nature of the Kalahari makes logistics and maintenance challenging, specifically for researchers, who aim to minimise the time they spend on data capture. Careful logistics planning for transportation, installation and servicing must be reviewed, while taking into account the diverse wildlife and vegetation in the region that may interfere with accuracy. Finally, ensuring the sustainability of power sources, such as solar panels or batteries, amidst the variable sunlight and energy demands, presents significant problems for long term-monitoring efforts. Studying existing and emerging innovations efforts creates an avenue from which a solution can be developed.

2.2.1 Environmental Considerations

The Kalahari can be described as an arid savanna desert [1]. According to Cui, the Kalahari is "characterized by [both] hot summers and winters", with reliable "all year-round sunlight" [2, p. 111]. However, van Rooyen highlights that the biome is still susceptible to sporadic rainfall and sandstorms [1]. This confirms existing beliefs that the landscape in the Kalahari provides both opportunities and challenges for the development of a compact engineering system. While the regions' vast expanses, sunlight, and low human population offer ideal conditions which can aid researchers, it is hindered by the sporadic nature of the weather [2]. Understanding these concepts provides links for innovative solutions, and according to Keith, "the risks and benefits of engineering are not simply an objective property of the technology, they depend on the way it's used" [3, p. 13]. With global climate change predictions indicating that desert-type regions will experience an increased frequency of extreme events, a clear understanding of the potential region of implementation is required [1],[2]. Evidently, striking a balance between safeguarding technology against environmental damage and harnessing the environment's inherent advantages is salient for effective implementation.

An engineering system becomes futile if it is not sustainable; prioritizing longevity over cost can be a better course of action for engineers working in harsh terrain [2]. Van Rooyen corroborates this, highlighting that in such environments with extreme weather conditions, rugged landscapes, and limited access to resources, investing in durable, environmentally-friendly solutions becomes imperative [1]. Therefore, by ensuring longevity and resilience in an engineering system, notwithstanding increase in cost, continuous data collection can be implemented and, therefore, contribute to a more robust research project.

Keith underscores the absence of a singular solution, stating 'there is no magic bullet' [3, p. 7], in designing systems for harsh terrains. Nevertheless, he juxtaposes this by highlighting the evolving capabilities of engineers in shaping the planetary environment, facilitating greater accessibility to integrating technology with wildlife management [3, p. 7]. This viewpoint finds resonance in the work of Cui, who, although primarily focused on remote sensing of vegetation in the Kalahari, demonstrated the feasibility of creating a controlled environment within the biome. By simulating finite spatial scales and adjusting for potential vegetation growth, Cui's study highlights our capacity to navigate complex ecosystems without affecting the natural order of the existing environment [2].

2.2.2 Drongo Species

The Fork-tailed drongo (Dicrurus adsimilis), a species found in various habitats across sub-Saharan Africa, is a black-bodied bird with a distinctly fork-shaped tail, reddish eyes, and a hooked bill. They nest high in the branches of trees and the female lays between 2 and 5 eggs, which hatch after a short period of approximately 15 to 18 days [4]. Fork-tailed drongos are known to be highly territorial, aggressive birds that attack anything that imposes on their territory [5]. While they are primarily diurnal birds, their activities do extend into the early evening and dusk at times of low visibility. Key activities include social behaviour, roosting and foraging for food.

2.3 Integration of Electronic and Hardware Components into Avian Environments

The integration of electronic and hardware components into avian environments for monitoring has become a growing aspect of research in recent years. The impact of such interventions on the birds' behaviour can be studied through examining existing research to comprehend the implications of placing man-made structures into these natural environments.

2.3.1 Monitoring Equipment as Structural Disturbance

In pursuit of monitoring avian populations, monitoring equipment can sometimes act as a form of structural disturbance within the birds' natural habitat. While the primary aim of this equipment is to gather data on the birds' behaviour, its presence can inadvertently alter the physical and social environment for the species, resulting in data that may be inaccurate to the species. Gill states that 'The principal way in which human presence can impact wildlife is by altering the ability of animals to exploit important resources' [6, p. p9]. In the context of this review, monitoring devices are understood as evidence of human presence, and thus they have the potential to impede and cause disturbance to the natural environment, with their intrusiveness potentially leading to avoidance behaviours or increased stress levels among species [7]. Beale and Monaghan's [8] 2005 study on the decreased nesting success of seabirds in a tourist-frequented habitat further highlights the ecological consequences of human activity.

Furthermore, installing and maintaining monitoring equipment alone can cause disturbance to avian nests and foraging areas. Such disturbance, as well as the presence of equipment in the environment, has the potential to disrupt normal avian species behaviour such as courting routines, nesting behaviours and feeding routines [6]. In extreme cases, the introduction of monitoring equipment may lead to the abandonment of nesting sites and altered habitat selection.

Despite these potential impact, it is essential to acknowledge the importance of monitoring equipment in advancing our understanding of avian ecology and conducting conservation efforts. It is thus essential to pay careful consideration to the design, placement, and management of such equipment to minimise the potentially disastrous impact of human presence as stated by Gill. Fontúrbel et al. [9] present camera traps as a solution to minimise the disruptions detailed by Beale and Monaghan [7], proposing this method as cost-effective and long-lasting with almost no observer and structural interference. Further methods to minimise the intrusive nature of monitoring equipment include selecting unobtrusive mounting locations, minimising disturbance during installation and maintenance, and regularly re-assessing the long-term effects of the equipment on avian behaviour.

2.3.2 Effects of Artificial Light on Avian Behaviour

While direct human observation is the ideal form of avian observation, alternate measures must to be put into place to monitor the behaviour of diurnal species in an unobtrusive manner [10]. Richardson et al. state that "using surveillance cameras appears to be the most reliable method of identifying nest predators" [11, p. p287]. The artificial light at night (ALAN) caused using these cameras can however have a significant impact on avian behaviour.

ALAN has the potential to disrupt avian nesting behaviour by altering site selection. Richardson et al. [11] discuss nest abandonment as a frequent issue when cameras were set up early during nesting. Nocturnal light can attract or repel birds from potential nesting spots, as well as alter avian foraging by impacting insect availability and distribution. Artificial light, at various intensity and brightness, attracts insects which form the largest portion of the general avian diet. The light can often create insect hot-spots, benefiting some birds while disadvantaging others, as well as altering the geological structure of species nesting.

Similarly, ALAN can affect avian mating behaviour by disrupting courtship displays and impacting reproductive success. It interferes with visual communication signals during courtship rituals, negatively affecting the mating process.

Overall, it is imperative to ensure that whatever monitoring method put into place must account for the reaction, and subsequent action, of the species being studied. Birds are autonomous organisms, and in order to study them as organically as possible we must approach our research with sensitivity to their natural behaviors and environments, avoiding unnecessary disturbances and interventions.

2.4 Traditional and Modern Approaches to Avian Ecology Monitoring

2.4.1 Traditional Methods

Zwerts et al. [10] state that the most traditional approach to monitoring avian ecology would be through direct human observation. This publication compares this traditional methodology to more modern methodologies such as camera traps and acoustic sensors, which are discussed in (2.4.2) of this literature review.

There are various examples of visual bird surveying methods, such as the point count. According to Ralph et al. [12], a point count is where an observer is located at a fixed position for a fixed amount of time and count the number of birds in their line of site, in order to get a quantitative measure of bird populations. Most traditional methods are like this in the sense that they all have the caveat of relying on cooperation from the bird species and a skilled human observer for adequate data capturing [10].

2.4.2 Modern Methods

Several recent studies [10], [13], [14] show that there are many ways in which birds can be monitored without human intervention. For example, the use of a simple acoustic sensor such as a microphone to identify the presence of a bird species in an area [13]. S. Sharma, K. Sato, and B. P. Gautam suggest that "AI [artificial intelligence] algorithms are used to automate the detection and classification of wildlife sounds" [15, p. 1]. The AI and machine learning algorithms match detected bird sounds with those in a trained dataset for bird identification. S. Sharma, K. Sato, and B. P. Gautam also mention that attaining a large dataset for training AI models is a significant challenge. Moreover, inaudible sensors such as ultrasonic sensors are also a viable solution for presence monitoring as they can be installed near or inside bird nests to detect the motion of the bird [15].

Alternative to ultrasonic sensors, Merrick et al. [16] state that "LiDAR (Light detection and ranging) is a tool with potential for characterizing wildlife habitat by providing detailed, three-dimensional landscape information not available from other remote sensing applications". LiDAR's technology can be used to map out the 3D area regardless of the environmental illumination, which helps us understand the nocturnal behaviour of the bird. Another modern method for nighttime monitoring is to use a thermal camera to detect the body heat signature of the bird. D. J. McCafferty [17], however, mentions a thermal imaging pitfall for the use of birds like the Fork-tailed Drongo by stating that the technology is best suited for "captive birds that can be approached to within a few metres".

Burton et al. [18] state that camera traps which use infrared technology are most used animal monitoring system for animals in the modern era. R. Kays et al. [19] confirm this finding when they state that "camera traps are now a standard method for monitoring a variety of species over relatively large areas." Furthermore, Benjamin Murphy, an ornithology PhD student who was interviewed, stated that their current camera trap is "old, unreliable, [depletes] batteries too quickly and are too expensive to replace." Therefore, Benjamin Murphy's need for a low-cost camera trap and the monitoring industry's standardisation of them became the motivation for the corresponding section about camera traps.

2.4.3 Exploring the Role of Camera Traps in Avian Ecology

Rovero et al. [20] regard camera traps as "one of the most powerful tools for wildlife research." In terms of avian ecology, these cameras were used to gather data on the nest predators and for behavioural analysis between the adult and the nestling [21].

2.4.4 The workings and technicalities of Camera traps

Camera traps are a non-invasive data collection method in which cameras are placed in specified areas of interest and triggered to action without any human intervention. Several relevant sources [[10],[19],[20] mention that the cameras use infrared technology. This trap technology has all the common characteristics of a normal camera system such as limited battery life, storage space, resolution, environmental susceptibility, etc. However, since camera traps deal with wildlife monitoring the most important characteristics to consider are the trigger speed, field of view and the detection zone [22].

Table 2.1: Camera trap characteristic definitions

Term	Definition
Trigger speed	The overall responsiveness of the system is the time it takes for a camera system to take a picture after motion has been detected.
Field of view	Total range or area of a single frame.
Detection zone	Area embedded within the field of view in which the motion sensors are active.

As much as Table 1.1 illustrates the inherent characteristics of camera traps, they are also inherent limitations. This is because the presence and requirement of a trigger speed implies that behavioural data is lost or missed should the camera take too long to start capturing. This view is reinforced by Benjamin Murphy when he notes that the Browning Strikeforce Infrared camera trap that he is currently using is unreliable because of the slow trigger speeds. P. Palencia [23] suggests that a trigger speed that is too sensitive leads to a high number of blank images, because camera traps are constantly being activated by the surrounding vegetation.

Furthermore, knowing that the data is only collected when the bird is within the proximity of the sensors is a detection limitation [22]. This is because it is possible to have the bird within the frame of the camera with no data being captured because the sensors have not been triggered. More precisely, this implies that the detection zone is narrow and limited.

2.4.5 Types of Camera Traps

Savidge et al. [23] in the late 1980s showcased one of the first instances where the automated camera trap was used. This involved a film camera that was connected to an infrared transmitter and took a photo as soon as the beam was interrupted. Today remote, motion-triggered cameras are still used to capture images and videos of animals in their natural habitat. According to Robinson and Prostor's publication [24] this advanced technology of using a motion-activated system for a camera monitoring system is the ideal option.

In addition, P. Palencia [25] conducted a study of the five most used camera trap models that are available. Of these, the LAC (Ltl Acorn Ltl-5310 Series) was found to have the highest detection probability among bird groups. Palencia's report [25] highlighted that the LAC camera did not have the fastest trigger time, but it did have the largest field of view (FOV). This emphasises the importance of a high FOV when designing a camera trap for avian monitoring.

2.5 Infrared Monitoring

In the realm of nocturnal wildlife photography, infrared (IR) technology has emerged as a compelling alternative to traditional photographic methods, primarily due to its non-intrusive characteristics. This section delves into the foundational principles of IR technology, its advantages relative to conventional photography, and examines its inherent limitations as well as potential solutions regarding its application in the surveillance of avian species during nocturnal hours.

2.5.1 History and Principles of Infrared

Infrared radiation constitutes a segment of the electromagnetic spectrum, with frequencies extending from 300 GHz to 400 THz [26]. This form of radiation, which is imperceptible to the human eye, is often referred to as heat radiation due to its thermal emission properties. The discovery of infrared radiation, alongside other electromagnetic waves, was a significant scientific advancement of the 19th century [27]. It is a universal phenomenon that all living organisms emit heat radiation, a fact that underpins the operational principle of infrared imaging technologies.

The first use of infrared detection can be traced back to the 1920s with thermal detectors, notably thermocouples [28]. Initially, these devices did not generate an image; rather, they served to verify the existence and quantify the levels of infrared radiation. Subsequent enhancements led to the creation of the thermopile, an apparatus composed of multiple thermocouples connected in series [29]. Approximately four decades ago, a significant evolution occurred with the integration of various detectors with electronic readouts, culminating in the formation of detector focal plane arrays (FPAs) [28]. The refinement of FPAs, in conjunction with semiconductor technology advancements, caused a surge in the deployment of infrared imaging. This is attributed to the significant improvements in image quality, sensitivity, and operational efficiency.

The general working principle of infrared imagery is that it exploits the thermal contrast between an object and its environment to generate a visual representation. This process involves the translation of varying wavelengths, indicative of distinct thermal intensities, into a spectrum of colors. The resultant visual output, known as a thermogram, provides a visual form of the thermal differences in a color-coded format [30],[31]. This technique is instrumental in discerning features that are not visible in the spectrum of light detectable by the human eye, thereby providing a unique perspective for analysis and interpretation.

2.5.2 Benefits of using Infrared Technology

More recently, infrared imaging has emerged as a preferred method for nighttime photography. The efficiency and non-invasive nature of infrared cameras makes it particularly suitable for capturing images under low light conditions [30]. This preference is attributed to the limitations of visible light cameras in low-light conditions, which necessitate the use of supplementary lighting to achieve image clarity, thereby preserving the natural state of the environment under observation. This makes IR cameras a suitable and cost effective method of low light imagery.

Infrared imaging extends beyond mere detection, offering a sophisticated means of extracting distinct features of an object under observation [32]. This capability is pivotal in discerning the identity of the subject with precision. By isolating and analyzing specific characteristics, researchers can accurately determine the nature of the object being monitored. This aspect of infrared technology is particularly advantageous in ecological studies, where accurate identification is essential for monitoring biodiversity and behavioral patterns [33].

2.5.3 Limitations of using Infrared Technology

Infrared imaging, while beneficial, is not free of limitations. One of the challenges faced when using infrared imagery is terrestrial thermal emissions, which reduce the contrast, thus adversely affect the quality and fidelity of the infrared images [30],[34]. This decreases the signal to noise ratio of the image, as well as the sharpness, leading to fuzzy edges [35].

A method of overcoming these challenges is proposed by Xu et.al (2017), who recommends applying an algorithm which improves the contrast of an infrared image by enhancing the local contrast therefore achieving a sharper image. By applying this algorithm, the particular details of the image are more visible, and it works to reduce the SNR (Signal-to-Noise Ratio) of the infrared captured image [35].

2.5.4 Utilizing IR for monitoring birds

Mitchell et al. (2019) state that "cameras capable of detecting infrared (IR) heat signals may provide a more efficient and less invasive means of detecting nocturnal-roosting endotherms such as birds" [34]. The ability of IR imaging to identify the thermal signatures of animals, and in this case birds specifically, makes it suitable for night-time monitoring of birds [30]. The birds' environment will not be adversely affected by the presence of the IR camera.

Mitchell et al. (2019) concluded their study by saying that "Our results suggest that infrared thermography can be an effective and useful technique for detecting roosting birds and studying roosting behavior, as well as for population monitoring under certain conditions" [34]. This because IR cameras are a low cost, efficient and effective method of monitoring birds at night.

2.6 Enhancements in data storage and wireless communication in avian monitoring systems

2.6.1 The necessity for storage in wildlife monitoring systems

It is of the utmost importance to ensure that monitoring systems have an efficient data storage solution to maintain data integrity and accessibility. This requirement is emphasised in Robinson and Prostor's report [24] where the need to maximise the data collection implies the need for increasing data storage capacity.

2.6.2 Wireless Communications Technologies

S. Vadym [36] takes a practical approach to the argument of the best low-power wireless communication protocol by discussing the differences between the well-known Bluetooth Low Energy (BLE) and the ZigBee solution.

BLE offers a low-latency solution with power consumption that is much lower than the conventional, classic Bluetooth protocol [37]. Sources similar to [38] illustrate how BLE has a client-server model, with a distributed application framework dividing tasks between servers and clients. This view is further supported in the article as it mentions that BLE can send data "asynchronously and instantaneously whenever needed". This implies that devices will not first have to be paired with each other to facilitate communication, hence, making the model ideal for wireless data transfer in remote locations such as the Kalahari.

ZigBee by way of comparison has an even lower power consumption. S. Vadym [36] argues that ZigBee is the industry standard for applications that deal with remote monitoring. However, sources like [37] slightly contradict this by noting that ZigBee has no “sleep mode” compared to BLE. Hence, power utilisation over time can be saved and used more efficiently when using BLE for data transmission within wildlife monitoring systems such as camera traps. Furthermore, S.Vadym [36] also mentions that ZigBee has a lower data rate than BLE. This can be an alarming issue when transmission speed is a requirement, because successful observation requires the transfer of large data files such as HD images or video clips.

2.7 Power Systems

Understanding the biome, wildlife impact and system modules are a salient step in developing a suitable power system. According to Droisartt, who developed a compact camera system for plant monitoring, low power consumption is essential to avoid the need for heavy or bulky batteries. Further, creating a light weight, durable system creates a development platform from which autonomous operation, for long periods, can be improved. For example, Droisartt importantly mentions that deactivating components of the larger system, when not in use, is a necessary design feature to prolong the lifespan of the power module [39]. Existing methods corroborate this claim. The use of rechargeable batteries has acted as a useful, long-term solution to existing camera traps. With their light weight and small size, their ability to function independently has made this component a prevalent technology in wildlife monitoring [40].

However, Swann draws attention to the complexities of rechargeable batters. Their installation can be complicated, with wiring and improper placement of the charge proving difficult for researchers [40]. A study carried out by Barros in 2024, which sought an alternative to powering wildlife monitoring systems, investigated solar power. The aim was to create a fully autonomous power system that can be installed for an ornithologist, after which, maintenance and replacement can be neglected. This also mitigated the difficulty of obtaining new batteries in remote areas where a camera had a single power source: one camera was connected to the solar panel (model PW-3600 from Cuddeback), while the other camera used one set of 4 D-sized Varta alkaline batteries for the duration of the survey [41]. Interestingly, batteries were still used. This is common practice for solar powered systems. Unpredictable weather patterns, as discussed previously, necessitate an extra power source, adding to the expenses of a solar system intended for extended operation. But, this system must be calibrated to chosen equipment [39].

	Interpretation					
Coefficient	Power	Time	Days	Estimate (SE)	Lower CI	Upper CI
β0	battery	day	0	2.907 (0.123)	2.667	3.148
β1	Δsolar	day	0	0.171 (0.182)	−0.186	0.528
β2	battery	Δnight	0	−0.324 (0.165)	−0.648	0.001
β3	battery	day	Δ1	−0.012 (0.006)	−0.023	−0.001
β4	Δsolar	Δnight	0	0.005 (0.262)	−0.508	0.518
β5	Δsolar	day	Δ1	0.017 (0.009)	−0.000	0.035
β6	battery	Δnight	Δ1	−0.091 (0.008)	−0.106	−0.076
β7	Δsolar	Δnight	Δ1	0.071 (0.014)	0.044	0.098

Table 1.2: Solar Power and Battery Power Comparison

Table 1.2 is taken from Swann's study, and clearly displays the results of his study. Solar power has a large confidence interval (CI) of 0.528 and 0.518 for day and night activity, respectively. The battery confidence interval is the most consistent but, as previously examined, is difficult to implement and maintain [40]. Therefore, achieving a balance between solar and battery power is essential for establishing the most effective power system.

2.8 Conclusion

In summary, there are various current wildlife monitoring methods that can be drawn on and implemented for use in the Kalahari biome. An extensive review of both the environment and the impact of human behavior on an ecosystem was conducted, and decisions such as camera type, data storage and power were researched and analysed. The most prevalent and effective method currently available for bird monitoring was determined to be the the utilisation of a camera trap in conjunction with an infrared camera. Despite considerations of complexity, wireless transmission (BLE) was determined to be most suitable for storage and transmission of the system's data, with an external disk drive to alleviate time spent obtaining SD cards. Longevity and the cost of a functioning power system for camera trap models were investigated. There is significant literature available that analyses the deployment of a balanced solar/battery system, which is suitable for the habitat of the Drongo. This system must be adaptable and easily changeable to suit ornithologists in the field. From this literature review, several sub-modules were successfully studied. Merging and optimizing these modules into a singular system will provide a design from which a final solution can be created.

Chapter 3

Problem Analysis

The team responsible for conducting this report attended and participated in UCT's D-School activities, hosted by Ms Anne van Niekerk, prior to deciding which ornithological problem to tackle. These sessions not only built up the team's relationship, but also fostered the team's design and strategic mindset by engaging in activities that forced participants to break down the character of their fellow group members in order to know them better. Participants did this by drawing visuals of their respective partners relating to their personal life experiences, hobbies and aspirations. This process is symbolic to how a problem would be broken down, which was the same principle used when deconstructing all of the potential problems that were presented during the stakeholder presentation meeting.

The stakeholders for this project are the PhD Ornithologist students who presented various problems they are dealing with, from which the team could choose one to investigate and attempt to solve. It was emphasised here that the only way to materialise the solution to a problem is if the problem is holistically understood and thoroughly explored. Therefore, the team summarised all the problems presented on a white board using sticky notes. This was done to force the team to think critically and avoid rambling. Moreover, without hyper-focusing on the solution, the most interesting problems were highlighted. The group had found the Fork-tail Drongo camera monitoring presented by Ben and the mass weighting of the large Southern Ground Hornbills showcased by Carrie the two most interesting problems. These issues presented a lot of possible design choices, but ultimately Carrie's problem was not undertaken because there already seemed to be a solution in play and optimisation was presented as the focus. The group was more drawn to implementing a new, redesigned solution to a problem.

Therefore, Ben's problem was the one that the group selected. His off-the-shelf camera trap was not personalised to his needs, therefore it was critical that the problem be broken down and analysed from as many different angles as possible before narrowing in on a solution. This was the principle that Ms van Niekerk demonstrated in the corresponding D-School sessions, as the group went on to build a draft of the solution using Lego after the solution had been broken down into its various subsystems using the sticky tape approach.

The subsystems that were initially decided upon were power, sensing and the physical enclosure. After review, the following four subsystems were determined: power, sensing, user interface and hardware. The power subsystem would be responsible for ensuring that it encompasses a solar battery feature and that an regulated supply of power is provided to the system for a specified time. Thereafter, the sensing subsystem would be responsible for ensuring that the presented camera solution is a coherent one. The functionality of the sensing subsystem is highlighted by the user interface subsystem, which is responsible for allowing the user to interface with the system remotely. It is quite trivial to mention that an electronic solution without an enclosure is one raindrop away from failure. Therefore, the physical enclosure system is responsible for ensuring that the system is packaged in such a way that it can withstand environmental challenges whilst being aesthetically coherent with the natural environment. These subsystems form the cornerstone of the overall system solution presented in this report.

Chapter 4

Power(KGHMIC001)

4.1 Introduction

A camera trap system, that provides clear and reliable footage of Fork-tailed Drongos, needs to operate for long periods, without the need for maintenance by researchers. Evidently, the camera trap cannot consume large amounts of power and must be cheap and effective. Further, the system needs to be compact and benign to the birds. The design of a power sub-module for a solar-power monitoring system will ensure accurate and continuous data for an ornithologist. The power system is specifically engineered to provide a reliable and sustainable energy source for operating an ESP32 micro-controller unit. The implementation of two distinct cameras, designated for day and night capture, requires the activation of a separate infrared LED circuit during nighttime operations. These aspects are crucial for nocturnal and low-light observation of wildlife.

The primary objective of the circuitry should be to effectively combine power conversion and energy storage mechanisms. The system utilizes solar panels to harness solar energy. This energy is stored in rechargeable batteries, ensuring continuous operation during periods without sunlight. The solar power circuit includes voltage regulation to ensure stable power delivery and protect sensitive electronic components from fluctuations. Including a power management system is critical to monitor battery status, manage power distribution, and optimize charging and discharging processes. This feature allows users to freely observe the functioning of the device. Additionally, voltage cut-out and polarity protection are seamlessly incorporated into the design, creating a user-friendly circuit for the ornithologist.The power design acts as a black box, enhancing the modularity of the overall system. This allows ornithologists to easily swap out the camera trap, thereby maximizing flexibility in the field. The system's design considers the environmental conditions of the Kalahari, focusing on durability, reliability, and capability to manage thermal and mechanical stresses. The following sections detail requirements, components used, and the system's configuration and integration of the power circuit with the overall monitoring system.

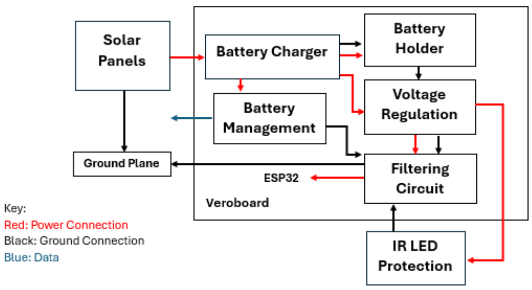

Figure 4.1: Power Sub-Module Overview

4.2 Requirements

4.2.1 User and Functional Requirements

Table 4.1 below specifies what the user expects the system to do at a high level. Forming the foundation for prototype development. The functional requirements included in the table are derived from the user requirements. Addressing all demands of the ornithologists, to ensure that the power section of the monitoring system is reliable and capable of operating autonomously in the Kalahari. They focus on optimizing the energy harvested from solar panels, ensuring the longevity and stability of the power supply, and maintaining system safety and compliance. The requirements further emphasize that there is integration between the software and sensing subsystems and the power design.

Table 4.1: User and Functional Requirements for the Power Module

User Requirements	Functional Requirements
Power Supply Stability and Compatibility: The power module must consistently provide sufficient power to support the camera trap system, reducing the time ornithologists spend in the field to repair and restore the power of a device.	**Supply 3.3 Volts:** Provide continuous 3V3 to power the ESP32 using solar energy. Additionally, a voltage divider circuit connected to the micro-controller provides visibility into battery management, thereby preventing issues associated with inadequate voltage supply.
Extended Operational Capacity: The power module should support a minimum of 5 days of continuous operation without recharging or battery replacement, to minimize field maintenance and ensure continuous monitoring over extended periods.	**Rechargeable Battery System:** In situations where solar energy is inadequate, incorporate a battery system to maintain the uninterrupted operation of the camera trap. Batteries must be rechargeable and supply the device at a rating similar to solar panels (3V3, 500 mA, 1.65W).
Multi-Device Support: Capable of powering multiple devices simultaneously without degradation in performance or stability of the output. Enables the system to accommodate various sensors and recording devices as needed for comprehensive monitoring.	**Maintain Supply Ratings:** Ensuring a power supply that delivers over 500 mA at 1.65 W in active mode and 300 mA at 0.1 W in sleep mode is crucial for operating the micro-controller while accommodating peripherals without overloading the system.
Daytime and Nighttime Operation: Camera footage is needed for the Drongo's activity throughout 24 hours. The power module must ensure camera activity is operational at this time.	**Infrared LED Circuit:** Power module must turn on 4 IR LED's at 7 PM.
Future-proof design: It's crucial for ornithologists that the power sub-module is a permanent solution, offering lasting flexibility for system upgrades over time.	**System Upgradability:** Include the capability to integrate additional power sources, expand battery capacity, or update power management software. Interchangeable components are emphasized, making the device flexible.
Compact: The device must be small and easily integrated into the field setup without burdening the mobility or installation process.	**Scaled Components:** An 80mm-by-80mm Veroboard will be used to hold circuitry. Additionally, 112mm-by-84mm solar panels complete a mobile power module.
Durability and Environmental Resistance The power module must be enclosed in a durable, weather-resistant casing that protects against environmental elements such as dust, heat, and moisture. Ensuring longevity and reliability of the overall system.	**Hardware Compliance:** The power module is engineered to conform to specific enclosure specifications. It features solar panels mounted on a 30 cm by 26 cm panel, with the internal circuitry securely housed within a protective wooden box.
Regulatory Compliance for Ornithologist and Wildlife: The power module must meet all applicable safety standards and regulations for electronic devices used in wildlife research settings.	**Polarity Protection and Voltage Cutout:** The IR LED circuit includes polarity protection to prevent damage to the device. Additionally, the charging module features overcharge protection to prevent overheating and potential fire hazards.
Minimize Cost of Device: The power module must be both effective and affordable, as ornithologists working in the field operate with limited budgets (Less than R500).	**Budgeted Circuit:** A simple, effective circuit will be designed within a budget of R500, ensuring cost-efficiency.

Utilizing defined requirements facilitates the design process by providing a clear framework and direction. This ensures that all design decisions align with user needs and functional expectations.

4.3 Design Process

4.3.1 Solar Panels and Battery

For efficiency and simplicity, the power module is designed to supply the ESP32. The micro-controller, in turn, powers two cameras and a PIC sensor. This approach simplifies the management and maintenance of current and power ratings. Attention is solely focused on the micro-controller specifications. This focused strategy facilitates a design optimized for a single, clear objective: providing continuous and stable power to the ESP32. Table 4.2 displays the fundamental power considerations that define the power module.

Table 4.2: Power Ratings of ESP32 for Sleep Mode and Active Mode

ESP32 Mode	Voltage (V)	Current (mA)	Power (W)
Active	3.0 – 3.6	500	1.65
Sleep	3.0 – 3.6	150	0.1

Using this information, practical solar panels and batteries can be selected. The ESP32 operates in cycles. The cycles are approximately 10 seconds, during which 100 mA is drawn. Therefore:

$$\text{Energy Consumption per Cycle} = 100\,\text{mA} \times 10\,\text{s} = 1000\,\text{mAs}$$

$$\text{Energy Consumption per Hour} = 6 \times 1000\,\text{mAs} = 6000\,\text{mAs}$$

$$\frac{6000\,\text{mAs}}{3600\,\text{s}} = 1.66\,\text{mAh}$$

The solar panels must supply at least 1.66 mAh. In the absence of solar energy, the batteries must fulfill this requirement.

$$1.6\,\text{mAh} = 1 \times 18650 \text{ battery (3.7V)}$$

Calculations for determining the size of solar panels required in the Kalahari Desert based on power consumption needs:

$$\text{Size of Solar Panel} = \frac{\text{Power of ESP}}{\text{W/m}^2 \text{ in Kalahari}}$$

As determined in the literature review, the solar energy in the Kalahari is, on average, 20 W/m^2. Therefore, the solar panel must be 82.5 cm^2. However, factoring in shade, periods with low sunlight, the efficiency of solar panels, and the availability of components, a 112 mm-by-84 mm solar panel was selected. These solar panels capture a sufficient amount of solar energy that meets the requirements of the circuitry. Selecting a 6V, 200mA solar panel was examined:

$$\begin{aligned}\text{Power Demand (mWh)} &= \text{Current (mAh)} \times \text{Voltage (V)}\\ &= 1.66\,\text{mAh} \times 6\,\text{V}\\ &= 99.6\,\text{mWh}\end{aligned}$$

$$
\begin{aligned}
\text{Daily Energy Requirement (Wh)} &= \text{Power Demand (Wh)} \times \text{Effective Daylight Hours} \\
&= 0.0996\,\text{Wh} \times 12\,\text{hours} \\
&= 1.11952\,\text{Wh}
\end{aligned}
$$

$$
\begin{aligned}
\text{Solar Panel Output (Wh)} &= \text{Panel Power (W)} \times \text{Sunlight Hours} \\
&= \frac{200\,\text{mW}}{1000} \times 12\,\text{hours} \\
&= 0.2\,\text{W} \times 12\,\text{hours} \\
&= 2.4\,\text{Wh}
\end{aligned}
$$

$$
\begin{aligned}
\text{Is One Panel Sufficient?} &= \text{Daily Output (Wh)} \geq \text{Daily Energy Requirement (Wh)} \\
&= 2.4\,\text{Wh} \geq 1.1952\,\text{Wh} \\
&= \text{True}
\end{aligned}
$$

Accounting for the efficiency of solar panels and the importance of continuous operation of the device, two solar panels are selected and connected in series.

Table 4.3: Specifications of Power Supply Components

Power Device	Current (mA)	Voltage (V)	Power (W)	Size (cm^2)
18650 Battery	400	4.2	1.68	12
Solar Panel	200	6	1.2	94.08

Importantly, while the 18650 battery is nominally rated at 3.7V, it supplies up to 4.2V when fully charged. Employing solar panels to charge this battery during periods of sunlight ensures a reliable voltage supply to power the camera traps effectively, even during intervals without sunlight. These batteries can also be recharged with an external device, making them useful for remote research.

4.3.2 Battery Charger

The TP4056 is a suitable charging module for applications requiring efficient management and safe sharing of lithium-ion batteries. It features constant current/constant voltage linear charging, which is ideal for maintaining the health and longevity of batteries. The module is compact, making it easy to integrate, and additionally, the TP4056 module includes built-in thermal protection and automatic charge termination, protecting the battery from damage. This prevents overcharging and overheating. Table 4.4 displays the important characteristics of the module.

Table 4.4: TP4056 Specifications

Input Voltage (V)	**Maximum Charging Current (mA)**	**Protection Voltage (V)**	**Overcurrent Protection (A)**
5	1000	2.5	3

While the device's rated voltage is 5V, it can accept a maximum input of 6V. This makes it ideally suited for use with 6V solar panels, which may not always consistently provide a full 6V output. Furthermore, the charging current exceeds that supplied by the solar panel. Using the data sheet of the component, adding a 10K ohm resistor at in 2 (i.e. PROG) reduces sharing current requirements to 130mA. Examining Figure 4.2 below, it is evident that the power output of the solar panels decreases as the current drawn by the components increases. Therefore, reducing the current drawn from the module is crucial for ensuring successful operation. As stated, the

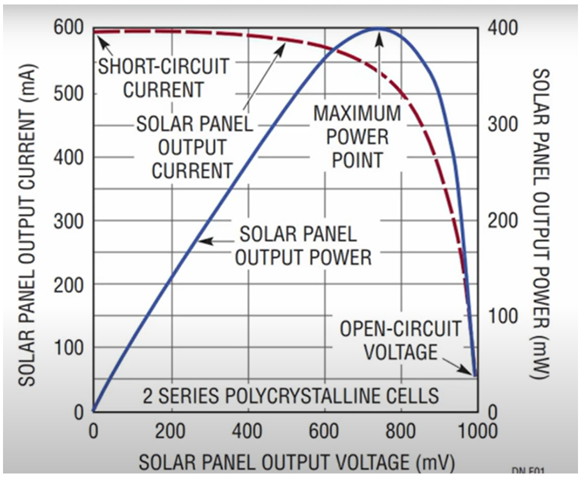

Figure 4.2: Solar Panel Ratings Curve

module incorporates under-voltage protection, which cuts off the charging current if the battery voltage drops below a certain threshold and over-charge protection circuitry, which monitors the battery voltage during the charging process. However, this only protects the battery, and not the other circuitry. Further protection needs to be designed and included in the power sub-module.

4.3.3 Battery Monitoring and Voltage Cutout

Battery management and voltage cutout are essential for maintaining circuitry health and safety, particularly in devices that rely on rechargeable batteries. Battery monitoring ensures that parameters such as voltage, current, and temperature are within safe operational limits. Meanwhile, cutoff mechanisms protect the circuit from conditions that could lead to overcharging and deep discharging. Using an analog in of the ESP, voltage management and cutout can be achieved.

Since the battery outputs 4V2, a voltage divider circuit is needed to output 3V3 to pin A0 of the ESP.

$$V_{\text{out}} = \left(\frac{4.2 \times 100\,k\Omega}{27\,k\Omega + 100\,k\Omega} \right) = 3.3\,V$$

To obtain the battery level, simply read the voltage on GPIO33 using the analogRead() function.

```
analogRead(0);
```

This voltage level can be externally monitored by an ornithologist via a webpage. If it falls below the required threshold, the ESP must be shut off, indicating a system error that researchers need to address. Therefore, although the power module functions as an isolated unit among the sub-modules, it primarily interacts only with the ESP32 and the associated software.

4.3.4 Voltage Regulation

Voltage regulation is important to the ESP32, which requires stable voltage levels for optimal performance and reliability. Proper voltage regulation ensures that the ESP32 operates within its specified voltage range, preventing damage due to voltage fluctuations. Using a typical linear voltage regulator to drop the voltage from 4.2V to 3.3V is not advisable. As the battery discharges to, for example, 3.7V, the voltage regulator may not function effectively due to its high cutoff voltage. This situation can lead to insufficient power being supplied to the ESP32, causing system instability or failure.

A low-dropout regulator (LDO) is required. The MCP1700 is an effective LDO, which is often used with the TP4056 sharing module.

Table 4.5: MCP1700 Specifications

Input Voltage (V)	**Voltage Drop (mV)**	**Output Voltage (V)**	**Output Current (mA)**
2.3 - 6	170 - 500	1.2 - 5	250 - 600

Table 4.5 indicates the regulator can accept voltages in a range suitable for the system's requirements. The regulator will receive a maximum of 4V2 from the battery charging module, and a minimum of 3V7. For an optimal design choice, the MCP1700 regulator demonstrates sufficient capability to meet the ESP32 power requirements:

- At an input voltage (V_{in}) of 4.2V with a voltage drop (V_{drop}) of 0.5V, the output voltage (V_{out}) is calculated as follows:

$$V_{\text{out}} = V_{\text{in}} - V_{\text{drop}} = 4.2V - 0.5V = 3.7V.$$

  At this operating point, the output current is 600 mA, adhering with the requirements of the ESP32.

- Additionally, at $V_{\text{in}} = 3.7V$, $V_{\text{drop}} = 0.4V$, the output voltage is:

$$V_{\text{out}} = V_{\text{in}} - V_{\text{drop}} = 3.7V - 0.4V = 3.3V,$$

  with an output current of 500 mA. This configuration ensures that even at the minimum voltage input, the ESP32 is adequately powered.

Thus, the MCP1700 is confirmed as a suitable design choice for reliably powering the ESP32.

4.3.5 Filter Circuitry

For optimal performance of Low-Dropout (LDO) regulators, it is recommended to employ both a ceramic and an electrolytic capacitor in parallel between the output voltage (V_{out}) and ground (GND). This setup helps to stabilize the output by smoothing voltage fluctuations and peaks. In this configuration:

- A $100\mu F$ electrolytic capacitor is used for its ability to handle higher voltage spikes and provide better long-term stability.

- A $100nF$ ceramic capacitor is included for its superior response to high-frequency switching noise, thereby enhancing the overall noise suppression.

This combination of capacitors ensures that the LDO maintains a steady output voltage under varying load conditions, thus justifying the choice of both types of capacitors for their complementary benefits in voltage regulation. An LTSpice simulation can be executed to prove the necessity of the capacitors, and further test that the correct capacitor values are used.

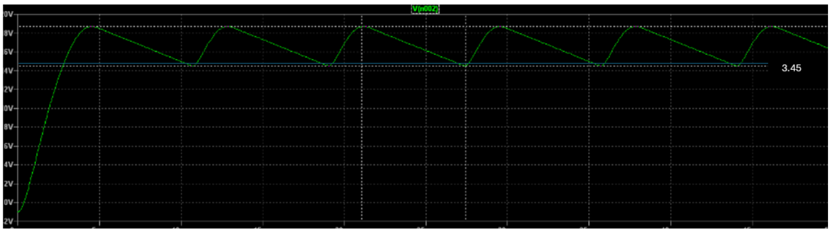

Figure 4.3: Capacitor Smoothing LTSPICE Simulation

The blue plot in Figure 4.3 corroborates that including capacitors in parallel provides a smooth output of 3V4.

4.3.6 Infrared LED Circuitry and Polarity Protection

As previously stated, an additional requirement of the sub-module is to power an Infrared (IR) LED circuit for nighttime activity. Using four TSAL6000 Vishay LEDs for nighttime vision is highly effective for monitoring the fork-tailed drongo from a close distance. These LEDs are known for their high radiant intensity and narrow beam angle, making them ideal for targeting specific areas with illumination.

Table 4.6: TSAL6000 Specifications

I_e (mW/sr)	ϕ (deg)	λ_p (nm)	t_r (ns)	V_{drop} (V)	V_{rev} (5V)
170 ± 10	10	15	-	1.2	5

Table 4.6 displays the important specifications of the didoes. The cameras utilized for footage capture will operate at no more than 2 meters from the bird. Therefore, given:

- Radiant Intensity (I): $17\,\text{mW/sr}$ (per LED) $\times 4$ LEDs $= 68\,\text{mW/sr}$
- Distance (d): $2\,\text{m}$
- Beam Angle (θ): $10^\circ = \frac{10\pi}{180}$ radians

Calculating the Illuminated Area (A):

$$A = 2\pi(2)^2\left(1 - \cos\left(\frac{10\pi}{360}\right)\right) \approx 0.48\,\text{m}^2$$

Calculating Illuminance (E):

$$E = \frac{68 \times 10^{-3}}{0.48} \approx 0.1417\,\text{W/m}^2$$

The area of illumination is suitable for the size of the Fork-tailed Drongos, and the illuminance is compatible with the chosen IR cameras.

The IR LEDs are rated with a 5V reverse voltage, which provides polarity protection for the micro-controller. In scenarios where batteries are reversed or connections are misplaced, the reverse voltage is insufficient to surpass the diode's threshold, as $5V > 4.2V$. Consequently, the ESP32 is protected. However, the diode's voltage drop of 1.2V presents limitations. By connecting the diodes in parallel with the voltage line to the ESP32, the voltage requirements should be met. If not, a separate buck boost converter can be designed for the circuit. It is crucial, therefore, to operate this circuit primarily during nighttime conditions.

Additionally, current-limiting resistors of 10 ohms must be placed in series with each diode to safeguard the devices. Calculating the resistance as $R = \frac{V}{I} = \frac{4.2-1.2}{500} = 6\,\text{ohms}$, using a 10-ohm resistor is deemed acceptable despite the minor difference.

4.3.7 Final Schematic

All circuitry from the design process can be integrated into a single design, to act as the guide from which a prototype can be constructed.

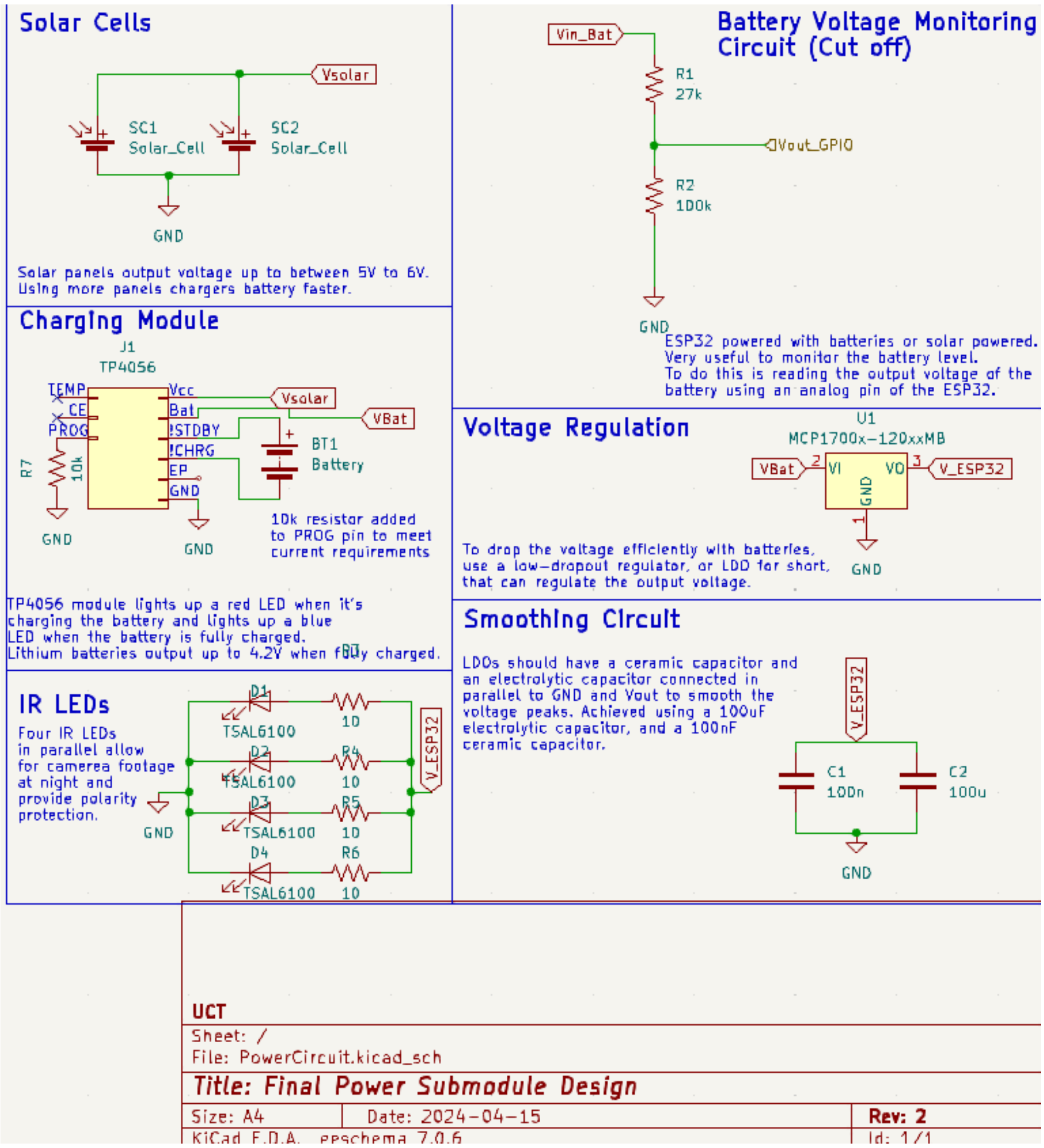

Figure 4.4: Power Sub-Module Final Schematic

4.4 Acceptance Test Procedures

Before construction begins, a set of Acceptable Test Procedures (ATPs) must be developed. These ATPs will establish a framework to evaluate the device's effectiveness. The testing framework will concentrate on Unit Testing and User Acceptance Testing. Each component of the power module will be tested, followed by comprehensive system testing to ensure it meets all the ornithologist's requirements. Importantly, for tests, solar cells are only used for PS-1 to check and prove their functionality. Thereafter, an oscilloscope is used to generate a variable DC voltage similar to what the solar panels would supply.

4.4.1 Unit ATPs

Table 4.7: Unit ATPs and Test Results

No.	**Test Description**	**Acceptance Criteria**	**Test Result**
PS-1	Charging battery. Place the uncharged battery in the holder and leave it to charge.	Battery charges to 4.2V.	**Passed**.
PS-2	Polarity protection for battery.	The charging module does not turn on when the battery is placed in the opposite direction (no red light).	**Passed**: Battery charger was off.
PS-3	Overcharging protection for battery.	Charging module does not turn on when two batteries are inserted into the holder (no red light).	**Passed**: Battery charger was off.
PS-4	IR circuit does not affect the current of devices.	When the IR circuit is configured, the current into ESP32 must still be 500mA.	**Passed**: Current varied between 450mA and 550mA, which operates system as expected.
PS-5	IR LEDs provide polarity protection for ESP32.	When wiring to ESP32 is flipped, the device must not turn on.	**Passed**: ESP32 off.
PS-6	Voltage regulation occurs.	Voltage into ESP must be 3.3V and smooth. (Test using the oscilloscope.)	**Passed**.
PS-7	Battery management.	Voltage going into the circuit is observable.	**Passed**: Voltage levels of the device are observable.
PS-8	Voltage cutout functional.	Circuit can be turned off when voltage drops below the threshold.	**Failed**: Turning off power module via ESP32 is ineffective.

4.4.2 User Requirements ATPs

Table 4.8: User Requirements ATPs and Test Results

No.	Test Description	Acceptance Criteria	Test Result
PS-9	Conduct load testing under varying conditions to simulate real-world usage.	Solar panels provide sufficient power when exposed to solar energy which does not fall below 4.2V in a 10-minute period.	**Passed**: Voltage supplied from panels does not drop below 4.2V in moderate sunlight.
PS-10	Run power circuitry, continuously, without recharging batteries for 1 hour.	System maintains functional operation and power output levels above the minimum required for 1 hour.	**Passed**: Battery can maintain a charge for periods.
PS-11	Connect the maximum number of supported devices and measure output stability and device performance.	All devices operate correctly with no observable reduction in power quality or system stability.	**Passed**: Power rating of ESP32 is unaffected when all devices connected.
PS-12	Monitor power delivery and camera functionality with IR LED circuit on (nighttime) and IR LED circuit off (daytime).	The circuit provides 500mA to ESP32 when the LED circuit is connected and disconnected. (Facilitates nighttime behavior of the module.)	**Passed**.
PS-13	Evaluate the ease of integrating newer components or expanding existing capacities.	System supports upgrades or modifications without significant redesign or downtime. Cameras with similar ratings can be plugged into ESP32 and there is no observable change.	**Failed**: Interchanging peripherals of similar power ratings causes loading.
PS-14	For compactness, measure dimensions and weight and perform field setup simulations.	Module fits within specified dimensional limits and is easily deployable by a non-engineer.	**Passed**.
PS-15	Subject the circuit to environmental tests such as heat, dust, and moisture resistance. Testing in rooms of 30 degrees Celsius.	No functional deterioration occurs, and all hardware remains intact, including wiring.	**Passed**: Device operates as expected in dusty, hot, and wet environments.
PS-16	Compile and review production and operational costs against Bill of Materials (BOM).	Total cost does not exceed R500, ensuring affordability.	**Passed**.

There is no ATP for the user requirement, Regulatory Compliance for Ornithologists and Wildlife, however, as determined in the literature review IR light does not harm wildlife.

4.5 Testing and Recommendations

All circuitry was soldered on a veroboard. Doing this ensures the power module would be secure in a remote environment. It further means the circuit is easily transportable.

Based on the design process, a functional prototype was constructed and subsequently tested against the Acceptable Test Procedures (ATPs). Table 4.7 and Table 4.8 indicate that two ATPs were failed, namely PS-8 and PS-13. While using the ES32 to monitor voltage was successful, attempting to turn off the whole system when voltage started to drop. The ESP32 was unable to control the power circuit effectively.

The power module was initially designed to provide uninterrupted power, which led to the omission of a switch that the ESP32 could activate to cut off power when voltage levels are low. Although this design choice does not mean the power system is ineffective—as declining voltage levels can still be monitored and an ornithologist can manually replace the system as necessary— it does mean the design can be improved. Integrating a MOSFET connected to the ESP32, linked to both the battery and solar panel, would provide a more effective solution. This setup would allow for automatic disconnection of power, better meeting the system's requirements.

Furthermore, the failure observed in test PS-13 can be attributed to the inflexible design of the circuit. Voltage, power, and current ratings for each peripheral were meticulously calculated to align with the ESP32's specifications. This design approach, while effective for the specified cameras, limited the compatibility with other devices. Although the circuit remains functional and deployable for its intended use in the field, modifications to the individual components of the power module will be necessary to accommodate the swapping of peripherals. In a future design for ornithologists, it is advisable to use components that can have their ratings changed on the device, allowing for immediate altercations as needed.

All other ATPs were passed and results for important tests can be observed below:

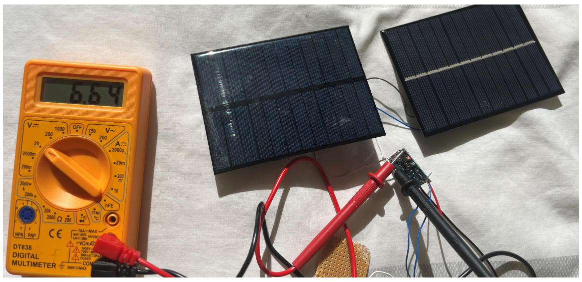

Figure 4.5: Solar Panel Continuous Output Voltage

Figure 4.5 illustrates that PS-9 was passed, and subsequent charging tests. While the voltage outputted from the solar panels varied between 5V5 and 6V7, it did not drop below 4V2. The battery charger was charged, indicative of the illuminated red light, and the rest of the circuitry was powered. Importantly, the solar panels were in regions of shade and dust, confirming panels are capable of operating effectively in desert-like regions.

Disconnecting the solar cells, and simulating periods of no sun, the battery voltage was tested at the input and output of the regulator. This test was conducted with the LED circuit connected. A value exceeding 3.7V at the input and 3.3V at the output indicates that both the current and power requirements are being satisfactorily met.

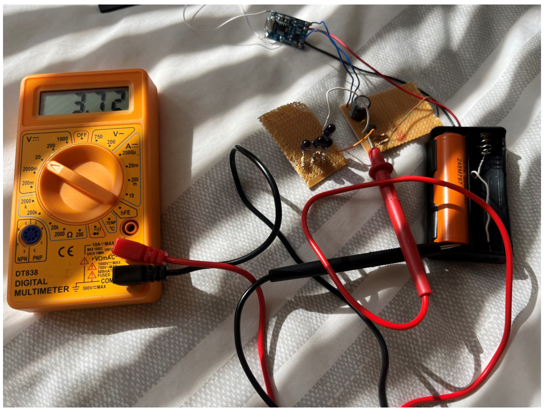

Figure 4.6: Battery Output

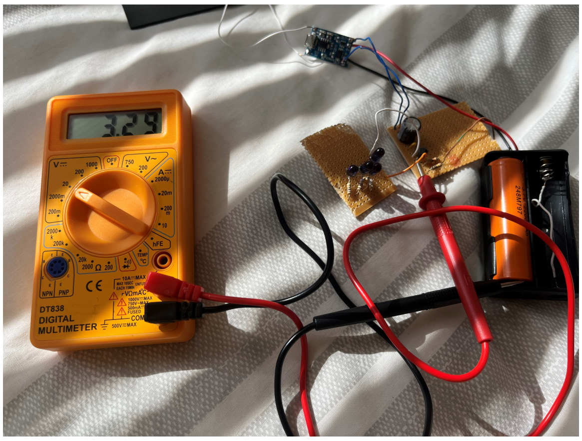

Figure 4.7: Voltage Regulator Output

Figures 4.6 and 4.7 demonstrate that the power circuit successfully met its requirements. The designs needed to provide 3V3, 500mA supply to align with the power specifications of the ESP32, and these criteria were fulfilled.

4.6 Conclusion

The objective of the power sub-module design was to supply sufficient voltage to an ESP32. This was accomplished through a comprehensive design process and implementation. Testing and validation confirmed the module's capabilities.

The device uses solar energy as its primary power source, complemented by a battery backup system integrated with a charging module. It incorporates essential protections against low voltage, overvoltage, and polarity reversals. Additionally, the circuitry features a battery management section that enables monitoring of the voltage supply, ensuring consistent functionality and stability.

This subsection on the power module demonstrates that through the integration of solar technology, ornithologists can reliably monitor the fork-tailed drongo without concern for camera power interruptions. This ensures continuous operation and data collection in field conditions.

Chapter 5

Sensing and Microcontroller (NHLSIY008)

5.1 Introduction

This sub-module serves as the operational spine of the project that is fueled by the previous power sub-module, chapter 4, and enhanced by the User-Interface sub-module listed in chapter 6. There are responsibilities that are both in the hardware and software domain that are taken care of by this sub-module in order get a viable solution for Mr Ben Murphy. The underlying operational difficulties listed in the problem statement are broken down in this section and a rigid, implementable solution is outlined.

5.2 Requirements and specifications

5.2.1 User Requirements

It goes without saying that a product is only as good as the satisfaction it provides its end-user. Therefore, the user requirements of this sub-module outline the performance and use of the camera trap that the end-user, Ben Murphy, needs. These user requirements are based on the problem statement as well as direct feedback from the user.

Table 5.1: User Requirements for the Sensor Subsystem

UR-ID	**User Requirements**
UR-01	The camera needs to be able to capture images that are about 1m away from the nest.
UR-02	The camera needs to be able to identify the scales on the birds' legs.
UR-03	The camera needs to operate efficiently by triggering quickly when a bird is in sight.
UR-04	The camera needs to be cheap and cost-effective.
UR-05	The camera needs to run for 4 - 5 days.
UR-06	The camera needs to be able to take pictures of the birds at night and in low-light conditions.
UR-07	The system must be able to track when an image was taken.
UR-08	Images need to be easily accessible.

5.2.2 Requirement analysis

The requirement analysis of this sub-module can be separated into the functional requirements and the system design specifications. These are neatly tabulated in the corresponding tables Table 5.1 and Table 5.3. However, it is worth noting that functional requirements are different to user requirements in that they focus more on breaking down what the system ought to accomplish.

Table 5.3: Functional for Sensor Sub-module

FR-ID	**Functional Requirements**	**UR fulfillment**
FR-01	Adequate Focus Range without compromising on image resolution	UR-01, UR-02
FR-02	Good image resolution using low computational resources	UR-02, UR-04
FR-03	Motion detection sensor must be sensitive.	UR-03
FR-04	All modules that are used within the system have to have a sleep mode to comply with power sub-module calculations to last 4-5 days.	UR-05
FR-05	Images to be stored in an SD card that can be accessed wirelessly.	UR-08
FR-06	System cameras must have infrared capabilities.	UR-06
FR-07	System needs to have a sensitive light sensor to be able to know when the camera must be on night-mode.	UR-06
FR-08	System needs to be able to calculate and maintain real-time.	UR-07

Table 5.5: Sensor Subsystem Specifications

SP-ID	**Specifications**	**FR fulfillment**
SP-01	Focus range of camera module needs to be greater than 1m	FR-01
SP-02	Camera system has to have FOV that is at least greater than 38.4°.[1]	FR-01 FR-02
SP-03	The trigger speed of the camera needs to be shorter 0.22s.	FR-03
SP-04	The camera system excluding the enclosure and the power system needs to cost less than R1100.00.[2]	n/a
SP-05	All modules that are used within the system have to have a sleep mode to comply with power system calculations for the system to be able to 5 days.	FR-04
SP-06	The camera needs to not have an IR filter when operating at night.	FR-06
SP-07	The system must include a robust real-time clock in which the time is always being tracked regardless of whether the system has power or not.	FR-08
SP-08	System needs to have WiFi or BTLE to be able to host a web-server in which the SD card contents can be read from.	FR-05
SP-09	System light sensor has to have a minimum sensitivity of 1 lux.	FR-07
SP-10	System MCU must have good flash memory (>2mB) and processing speed (>100MHz) to be able to simultaneously handle modules and web-server.	FR-01, FR-02 FR-03, FR-07

As seen from the previously illustrated tables, the listed functional requirements are somehow directly or indirectly linked to the user requirements. This is purely because the system needs to perform in such a way as to ensure that the user requirements are met. Moreover, the specifications are then easily linked to the functional requirements as seen in Table 5.3. The big idea behind the specifications is that they are merely a manner of quantifying the underlying functional requirements so that the system can be properly tested.

Moreover, note that the User Interface sub-module deals with the full web-server integration, however, this sub-module just ensures that web-server hosting is a possibility for easy access to SD card. (SP-08)

5.3 Sub-module objective

The below block diagram is a high-level design of the problem that is solved by this sub-module as per the requirements and specifications in the preceding section.

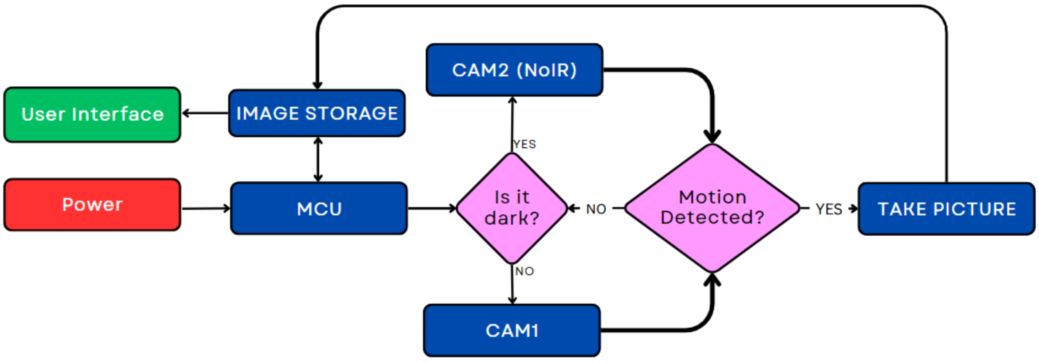

Figure 5.1: Sensor sub-module problem block diagram breakdown

Moreover, as seen in Figure 5.1 this sub-module interfaces directly with the User Interface and is powered by the power sub-module. There are various design choices that were make to further be able to amend this block diagram and produce one that is coherent and complete. This is intentionally meant to be a simplified version which will be amended after the design choices are illustrated.

5.4 Design Choices

The upcoming information is quite dense, however, should you wish to view the design choice process in a more visual, comprehensive flow diagram, click the following:

Sensor Design Choices Flow Diagram.

5.4.1 Communication Protocols

As seen in Figure 5.1, there are two types of system communication problems. There is a need to establish a communication protocol with the User Interface and Power sub-module. The second is the need to establish a communication protocol between the micro-controller and all the internal peripherals.

Communication protocols with external subsystems

The communication protocol with the power sub-module is quite a trivial one in the sense that it is a voltage value. This voltage is depended purely on the type of micro-controller that was used.

Therefore, as the ESP32-Wroom-32 was the selected micro-controller it requires a 3.3V line to interface between the subsystems. Note, subsection 5.4.2 elaborates further on why this specific micro-controller was selected.

The communication protocol between this sub-module and the UI sub-module had to be a wireless one because the user required easy access to the system and in the modern day there is nothing easier and more efficient than a wireless communication.

Therefore, various wireless communication protocols were investigated such as WiFi, Lora, GSM, BTLE and RF433. RF433, being a protocol that is susceptible to interference was found have a slow transmission speed which is not convenient for image data transmission. GSM was also removed as a potential choice as it is expensive to implement, therefore, violating the budget specification. It is also unsuitable for remote areas because of the protocol's huge reliance on cellular network coverage. LoRa on the otherhand was ruled out for a similar reason to RF433 in that the data transfer speed is slow. This left WiFi and BTLE as the two ideal wireless communication protocol solutions.

Nevertheless, WiFi's only caveat in this regard is that it increases the overall system's power consumption quite dramatically. However, this consumption can be managed accordingly should the relevant antennas only be in an active state when data is being transmitted and then off when idle. This is essentially alluding to having a micro-controller that has sleep mode functionalities which is touched more in subsection 5.4.2.

Moreover, BTLE does pose a slower data transfer speed to WiFi but at an advantage of a significantly lower power consumption. Thankfully, since Wi-Fi and Bluetooth both operate in the 2.4 GHz ISM band, devices tend to have both functionalities should they have the neccesary antennas for the one. Therefore, the design choice of the wireless communication protocol for this project is made simpler as concluding with both options is a reasonable and common choice as is the case with the selected ESP32-Wroom-32.

Internal subsystem communication protocol

UART, SPI, and ESP-Now via WiFi were among the protocols that were evaluated to find the best data transfer protocol between the slave ESP32-CAM and the master ESP32-Wroom-32. All of these protocols were supported by the camera board but some had some inherent limitations that made their use impossible. The UART0 lines for example were used for programming the cam board and the lines could only be used when powered by an external supply which made debugging a difficult process. On the other hand, a wireless protocol called ESP-Now was established for ESP micro-controllers and offered direct, fast, reduced-power communication over a wide range. However, this solution was tested but disregarded as a project requirement is to keep the power consumption to the minimum and ESP-NOW is still a WiFi based protocol. Therefore, although the SPI lines were blocked when the onboard SD card module was in use, the protocol proved to be the ideal solution because the plan was not to use the CAM's onboard SD card slot for storing the captured image data. Thankfully, SPI is a faster communication protocol than UART, therefore, making it a good choice for image data transfer.

5.4.2 Micro-controller selection

As previously mentioned, the ESP32-Wroom-32 was the micro-controller selected for this camera trap system because among other things the micro-controller has the ideal communication protocols that are needed in this project. Originally the ESP32-Wroom-32D micro-controller was preferred over its counterpart as it houses the exact same configuration with an added component of having extra flash memory. Moreover, the development board of the micro-controller was used as the underlying problem did not need a customised solution.

There were other potential microcontroller families with their respective types such as the Raspberry Pi, STM32, PIC and Arduino. In terms of the Raspberry Pi, the Pico W was found to be an ideal choice, however, it only had Bluetooth and no WiFi as a wireless communications protocol. The Pi 5 and the Pi Zero W were also looked at but quickly disregarded the moment it was found that the micro-controllers do not have a sleep mode function.

The Arduino family on the other hand are generally good for IoT applications because of their good interrupt handling configuration. However, the UNO and the Nano 33 IoT were looked at and disregarded because of their comparatively low flash memory of 256KB and 32KB respectively. Whereas the ESP32-Wroom-32 boasts 4MB with a possibility of customising it to 16MB. Moreover, any peripheral that is compatible with an Arduino is most likely to be compatible with the esp cam as well.

The STM32 on the otherhand was not chosen as the optimal solution because external BT and WiFi modules would need to be bought in to make the system function. This was also the reason why the ESP32-8266 was not considered.

Furthermore, the reason not to use the ESP32-CAM as the master micro-controller is because of the 512KB flash memory with very limited GPIO pins. The decision not to use PIC micro-controllers arose from the common requirement to use Microchip's proprietary IDE, namely MPLAB X, which is costly so they were disregarded.

5.4.3 Camera module selection

The unfortunate discovery that was found when selecting a camera module for the ESP32-Wroom-32 is that there is no wide variety of low-cost solutions in the market. The Raspberry Pi seemed to be the system with the most low-cost camera solutions that would be good for this project. However, as mentioned, they consume too much power to be regarded. Three possible cameras that were readily available, within budget and were investigated was the ArduCam Mega 3MP Spi Cam, OV2650 and the OV7675 camera. The OV7675 has a 0.3MP configuration so it is automatically invalid as it violated the user's needs to be able to identify the scales on the bird's legs.

A dual camera approach was then decided upon as one camera would be the daytime camera and the other would be the nighttime camera in which the nighttime camera had no infrared filter. A mixture of the ArduCam as the daytime camera and the ESP32 cam as the nighttime camera was used. This was done to ensure that the budget constrain is met because using two ArduCam would be depleting the budget. This is because a BO400 ArduCam currently goes for 25.99 dollars which at the current dollar to rand exchange rate as of 04/2024 equates to about R480.00. This unit price excludes the exuberant shipping costs or the marked up costs of getting the item from a 3rd party distributor and not directly from ArduCam.

The ESP32-Cam houses the OV2650 and because this camera is attached to a micro-controller it did indeed bring a slight level of complexity in making it work as expected for the final design.

5.4.4 Image file compression types

An examination of a variety of image formats, including BMP, PNG, and JPEG, to improve save storage space through system image compression was conducted. JPEG resulted as the most efficient and practical solution, despite the fact that it degrades image quality due to lossy compression. JPEG's main advantage is its significantly reduced file size, which is necessary for effective storage and transmission.

BMP, however, provides uncompressed, high-quality images which lead to files that are significantly larger. Therefore, rendering it unsuitable for this Fork-Tailed Drongo camera trap application as there is limited storage space. PNG offers lossless compression and transparency, but it creates larger files than JPEG, affecting transmission speed and storage capacity.

5.4.5 Embedded systems storage mediums for image

A detailed examination of internal and external flash memory as well as SD cards was done to find the best storage medium for image data within embedded systems. Image files can take up quite a bit of space depending on the quantity and the set resolution. The overall most inexpensive solution was found to be SD cards. Internal flash memory usually has a low, limited capacity and is, therefore, not recommended for storing big amounts of images. Moreover, external flash memory has a slightly less cost per mb compared to internal flash memory but this comes with a system integration complexity.

5.4.6 Motion sensor selection

The PIR HC-SR501 sensor was chosen as the most ideal motion sensor ahead of the HC-SR04 ultrasonic sensor.[3] The use of the PIR sensor is because it scans for heat signatures when trying to detect motion whereas the ultrasonic sensor scans for reflected sound waves. Hence, a lot of false positives can occur with using the HC-SR04 as things like leafs or moving brunches can trigger the camera system.

5.4.7 Light sensor selection

The sensitivity of the light sensor is of utmost importance. Therefore, the BH1750 was chosen as the ideal ambient light sensor.[4] As per the datasheet of the sensor it has a minimum lux detection range of 1 lux which is equivalent to the illumination experienced in a full moon night. The VEML7700 ulux sensor is a lot more sensitive than the BH1750 but it was not selected because that level of sensitivity to light is not required for this project. Moreover, the BH1750 is well documented compared to the former.

5.4.8 Real time clock module selection

For selecting the optimal Real-Time Clock (RTC) module, a detailed evaluation of the DS1307, DS3231, and PCF8563 was conducted. The DS3231 was determined to be the ideal solution as it offered superior accuracy because of its built in temperature compensated crystal oscillator. The DS1307, while cost-effective and widely used, lacks this temperature compensation feature, leading to less accurate timekeeping, especially under varying environmental conditions such as the ones experienced in the Kalahari. The PCF8563, though offering good performance, does not match the DS3231's accuracy and reliability for the same reason as the DS1307.

[3] Note that this sensor takes in a 5V input but it regulates it to 3v3. Therefore, the module's voltage regulator was easily bypassed with solder for the use of this system by simply looking at the schematic of the module.

[4] This sensor was not delivered by suppliers and an LDR comparator circuit was used to switch between the cameras.

5.5 Final Design

Overview

A summary of all the design choices and how the various choices interconnect to form the final design of the sensor sub-module can be illustrated by amending Figure 5.1 to show concluded selections. This is shown below:

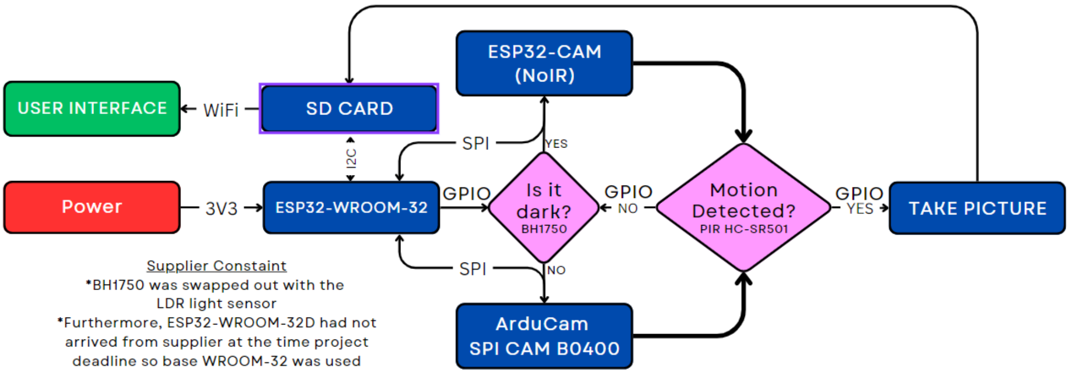

Figure 5.2: Sensor sub-module problem block diagram breakdown

Hardware layout

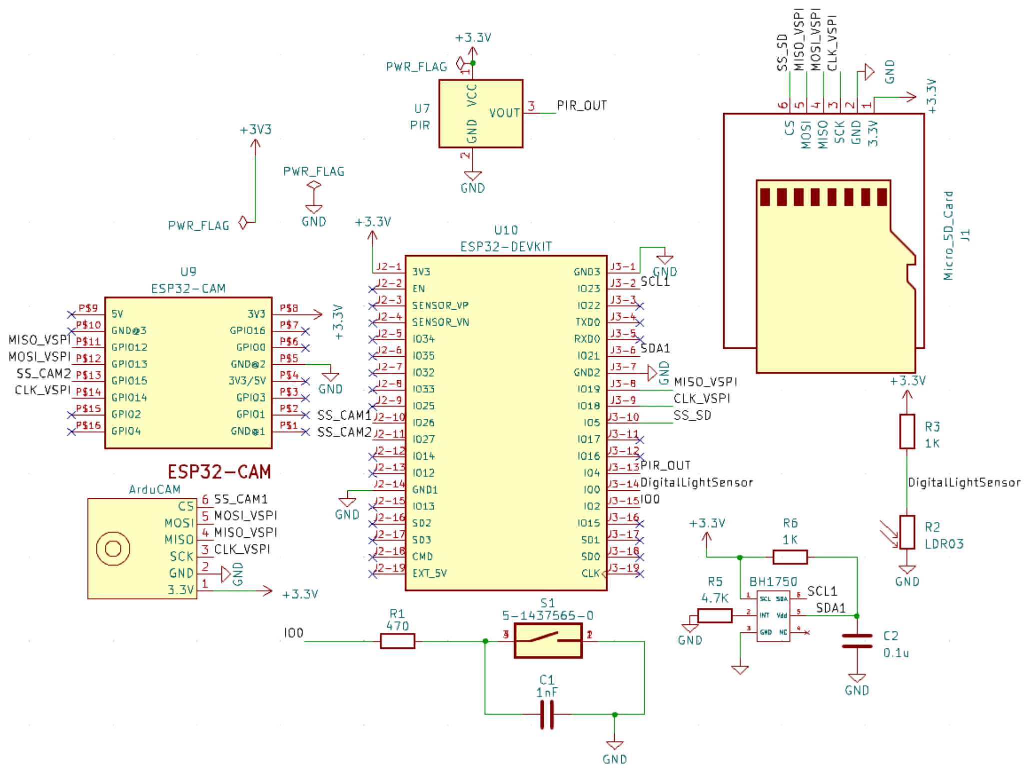

Figure 5.3: Schematic design of Sensor Sub-Module

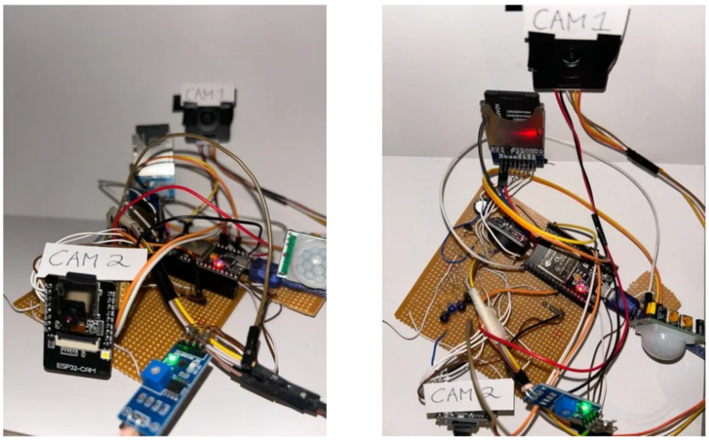

Figure 5.4: Veroboard implementation of design of Figure 5.3

Note that everything in Figure 5.4 except the ArduCam and the motion sensor was soldered onto the veroboard. The reason who not hard soldering these components was that they were often removed during testing. The soldering can be done on them by enclosure sub-module in chapter 7 once placed and positioned accordingly.

Coding Breakdown

The Arduino IDE was used and the relevant library needed to get the ESP32 on the IDE was found and install following this tutorial[5]:

Installing the ESP32 Board in Arduino IDE.

The coding breakdown of this final design can be separated into three distinct phases: **Library utilisation, Code initialisation and Code functionality.**

Library utilisation

Table 5.7: Sensor Subsystem Required Coding Libraries

Library	Function	Description
SPI.h	SPI Communication	Communication between master, SD card module and cameras
SD.h	SD Card Management	Contains needed functions to use SD card module
Wire.h	I2C Communication	I2C Communication with RTC module facilitation
Arducam-Mega.h	ArduCam Mega Management	Contains needed functions to use ArduCam
RTClib.h	RTC Management	Contains needed functions to use DS3231 RTC module

Code initialisation

Although any GPIO pin of the ESP32-Wroom-32 can be configured to facilitate SPI communication. The default ESP32-Wroom-32 has two default SPI lines, namely the HSPI and VSPI. Initially due to the faster nature of VSPI

[5]Note that IDE selection was not included in design choice section as it was deemed not relevant to the holistic Fork-Tailed Drongo camera trap problem. There are other IDEs such as VS Code with the relevant extensions that can be used as well.

over HSPI, it was deemed that the SD card module would be connected to the VSPI and the camera modules were then connected to the HSPI with different slave select lines depending on which camera is active. However, it was discovered that the ArduCam Mega library is configured in such a way as to only work with the default VSPI pins. Therefore, the code was amended to ensure that the three SPI devices use the same VSPI pins and have different slave select lines in which communication is properly facilitated between them. The main things that require to be initialised are the two cameras, the SD card module, the RTC module as well as the VSPI line itself.

The full code can be found in the git repository in the Appendix H to see this initialisation.

Code functionality

As mentioned, the sensor sub-module code in the repository is well commented. Therefore, this section only concerns itself with a high-level description of what the code aims to do. The overall goal should be clear now in that the status of the light sensor determines which slave select line between the cameras is active. Furthermore, an instruction to take a picture is sent to the master to tell the camera slaves that motion is detected. Therefore, this implies that there is also a status check on the GPIO pin connected to the PIR motion sensor.

5.6 Testing and Results

5.6.1 Acceptance Test Procedures (ATPs)

Note that since the implementation of the ESP32 Camera failed and a compromise to simulate its contribution was made, any camera related ATPs were tested solely using are ArduCam SPI camera module. Moreover, all connections between modules as listed in the ATPs are the same pin connections seen in Figure 5.3.

Table 5.9: Acceptance Test Procedures and Results

ATP-ID	Acceptance Test Procedures (ATPs)	Sp Tested	Pass/Fail
ATP-01	**Description:** Verification that the camera captures images when motion is detected. **Procedure:** Connect up the ArduCam SPI camera module to the ESP32. Initialise camera accordingly and connect the HC-SR501 motion sensor to the ESP32. This is not a test to see if image is saved to a storage medium so a LED is toggled for verification and a serial monitor message is printed. **Acceptance criteria:** LED goes on and image capturing notification is sent to serial monitor each time a person walks past the sensor.	SP-01 SP-02	Pass

Continued on next page

Table 5.9 – continued from previous page

ATP-ID	Acceptance Test Procedures (ATPs)	Sp Tested	Pass/Fail
ATP-02	**Description:** Verification that the camera images are stored on the SD card. **Procedure:** Connect the ArduCam SPI camera to the ESP32 and initialise the I2C SD card module. Capture an image and save it to the SD card inserted in the module. Then proceed to checking content of the SD card. **Acceptance criteria:** Captured image file is present on the SD card and not corrupted.	SP-03 SP-04	Pass
ATP-03	**Description:** Ensure the RTC module keeps accurate time even after losing power. **Procedure:** Connect the DS3231 RTC module to the ESP32. Set the time on the RTC module as the time at compile time, print it to the serial monitor and then disconnect power. Reconnect power and check time in serial monitor. **Acceptance criteria:** Expected time is printed in serial monitor.	SP-07	Pass
ATP-04	**Description:** Test that the system is able to enter deep sleep mode for power conservation. **Procedure:** Program the ESP32 to enter deep sleep mode after defining a timed wake up source. Measure the current consumption after after deep sleep function is called. **Acceptance criteria:** Significant reduction in current consumption when the system is in deep sleep mode.	SP-05	Pass
ATP-05	**Description:** Verify light sensor functionality and camera switching. **Procedure:** Connect a light sensor to the ESP32 and two cameras. Program the ESP32 to switch between the cameras based on whether the light illumination is below or above a lux. Thereafter, vary light conditions and take a photo with the camera in operation while printing the name of the camera in the serial monitor as the picture is taken. **Acceptance criteria:** Cameras switch appropriately when subjected to lighting similar to a full-moon[6].	SP-06 SP-09	Fail[7]
ATP-06	**Description:** Confirm the micro-controller handles cameras, sensors, and web-server operations simultaneously. **Procedure:** Connect cameras, sensors, and set up a web-server on the ESP32. Redo a camera or sensor ATP while web-server is on. **Acceptance criteria:** ESP32 is able to host function with web-server active without noticeable compromisation of the performance of the cameras and sensors.	SP-10	Pass

Continued on next page

Table 5.9 – continued from previous page

ATP-ID	Acceptance Test Procedures (ATPs)	Sp Tested	Pass/Fail
ATP-07	**Description:** Test the system's ability to host a web-server and access contents on SD remotely via WiFi. **Procedure:** Set up a web-server on the ESP32 and store files on the SD card. Access the files over WiFi from a remote device[8]. Verify access to files and the integrity of the data. **Acceptance criteria:** Files on the SD card are accessible via WiFi with no data corruption.	SP-08	Pass
ATP-08	**Description:** Verify that the camera module does not have an IR filter during nighttime operation. **Procedure:** Capture images using the ESP32-Cam with the removed IR filter in a dark environment with infrared LEDs for illumination. Access the visibility of the images. **Acceptance criteria:** Camera captures clear images in the dark, indicating no IR filter is present.	SP-06	fail[9]
ATP-09	**Description:** Check that the sub-module's total cost remains within the budget. **Procedure:** Sum the costs of all components used in this sub-module and ensure it is less than R1100. **Acceptance criteria:** Total cost is less than R1100 (see BOM).	SP-04	Pass
ATP-10	**Description:** Ensure the camera's trigger speed is consistently below 0.22 seconds. **Procedure:** Measure the time taken from motion detection to image capture using a stopwatch or timing function. Perform multiple tests to ensure consistency. **Acceptance criteria:** Average trigger speed is below 0.22 seconds.	SP-03	Fail [10]

5.6.2 Code Results

The code in its current capacity as listed in the repository and fulfills most of this submodule's objective. The ESP32-Wroom-32 part is the only caveat in the code as the SPI communication could not fully be completed so it was simulated accordingly. The incompleteness is not due to a design choice error but an issue that was discovered with using SPI communication to send over the image files. Theoretically this procedure should work but the configuration of the ESP32-CAM is in such a way that the ESP32-CAM uses its SPI lines for the onboard SD card

[6] Full moon = 1lux

[7] This this failed due to a number of reasons. Firstly, the ESP32-CAM is not fully operational. Secondly an LDR powered module was used as a contingency as the delivery of the ordered BH1750 ambient light sensor chip was cancelled on a short notice because of stock issue. However, camera switching works well.

[8] see git repository for web server implementation from UI sub-module

[9] The newer models of the Ov2650 ESP32-CAMs have the IR filter embedded in their front lens which make it nearly impossible to remove. (see Appendix B)

[10] The HC-SR501 was noisy, produced false positives and it has a minimum delay time of three seconds which caused measurement issues. A better interrupt structure should be implemented in the code for future variations to deal with this.

connector. Although an SD card in the ESP32-CAM slot was not the configuration files of the ESP32-CAM still have the communication line active. An attempt was made to try and change the configuration files, however, this could not be finished in because of the rigorous project time constraint. Suppliers also took long to deliver the micro controllers which further highlighted the issue on time.

5.6.3 Camera Testing

Arducam vs ESP32-CAM

Figure 5.5: Images taken from various distances of prototype bird using ESP32-CAM

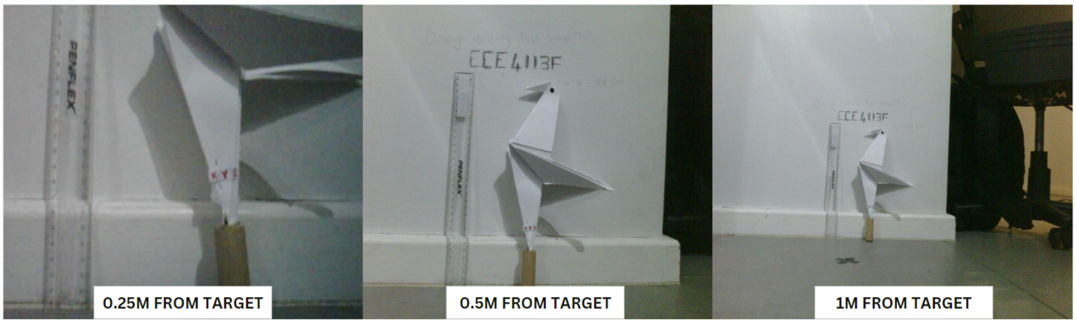

Figure 5.6: Images taken from various distances of prototype bird using ArduCAM

As seen from the test images taken above, both cameras quite clearly have a FOV greater than 38.4 degrees at a distance 1m away as was the minimum specification. This is because the cameras needed to cover a horizontal distance greater than that shown in Appendix A, which is the case as shown in Appendix C.

Furthermore, the ESP-32 Cam quite clearly fails to identify the fake scales (XYZ label) on the bird's legs in Figure 5.5. The ArduCam also struggles but the images do look a lot clearer. This visibility is significantly better seeing that the ESP32-CAM managed to darken the images even though the environmental illumination was kept at a constant.

5.7 Conclusion

This sub-module has not wholeheartedly completed its desired goals, however, there is a direction and a link that has been outlined in which all user requirements and specifications can be met. A major drawback that was experienced is that of not being able to fully test the night mode functionality of the camera because of the ESP32-Cam having an irremovable IR-filter. Nevertheless, the extent of the achievements outlined within the sensing and micro-controller ensured that the other sub-modules have a spine to work with.

Chapter 6

User Interface (BHMQAI001)

6.1 Introduction

The data collected by the camera trap system is required by researchers so that further analysis and subsequent action can be carried out. This data needs to be able to be retrieved from the camera trap, displayed on a user interface and transferred to the researchers' devices. The user interface subsystem within the camera trap system serves as the primary point of interaction between researchers and the overall system, facilitating data retrieval, analysis, and interpretation. Through a systematic design approach, the design and implementation of the interface will be carried out with the requirements in mind, ensuring accessibility to the data collected and a means to store it for further analysis.

The design process begins with determining user requirements and outlining functional requirements and design specifications, which are then used to make informed design choices regarding the micro-controller used, front-end design and system architecture implementation.

Throughout the design process validation is carried out through conducting various tests, which is then used to write up an acceptance test procedures analysis. These tests determine the system's performance, usability, and adherence to user requirements, validating the effectiveness of the design choices and the robustness of the final subsystem.

Following the design phase, the final system is implemented, integrating the chosen design elements to produce a cohesive and efficient user interface subsystem.

6.2 User Requirements

The user requirements detail the specific needs that the researcher has with regards to the user interface of the camera trap system. These requirements were gathered through stakeholder engagement in the form of online interactions with Ben Murphy, a PhD ornithology student with the Fitzpatrick Institute of African Ornithology, and tabulated in Table 6.1 below to form the foundation of the design and implementation of a subsystem that meets the needs of its intended user.

Table 6.1: User Requirements for the User Interface Subsystem

No.	User Requirements
UAS-1	**Usability:** The interface should be designed such that it is easy to navigate and understand.
UAS-2	**Data Retrieval:** Data retrieval should be conducted in a way that avoids disturbances to the birds' nests, enhancing ease of use and reducing the need for the researcher to climb the tree to retrieve the data manually.
UAS-3	**Data Transferal:** Since the images will be analysed at the different time and location, the user application must have an option to download the images onto the user's device.
UAS-4	**Data Storage:** The user interface should have some feature to clear the data off of the physical camera trap after it has been retrieved, in order to free up memory.
UAS-5	**Data Display:** The retrieved data and images should be displayed in an organised and understandable format on the user interface.

6.3 Requirements Analysis

Table 6.2 below presents the requirements analysis of the user interface subsystem of the camera trap system, partitioned into functional requirements and corresponding design specifications. The functional requirements were identified through a detailed analysis of the user needs, aiming to ensure the effective performance and usability of the user interface. Each requirement is paired with a specific design specification outlining the approach to be implemented to meet the respective requirement.

Table 6.2: Requirements Analysis

No.	Functional Requirements	Design Specifications
UAS-6	**Real-time responsiveness:** The interface should respond to user interactions and data requests within 5 seconds.	Caching mechanisms and asynchronous loading of data shall be employed to optimize loading times and minimize delays in data retrieval.
UAS-7	**Accessibility across devices:** The user interface should be accessible from various types of devices.	An appropriate platform will be chosen to ensure accessibility across devices.
UAS-8	**System Health:** The designed architecture must include features for observing the health of the other subsystems.	The user interface will include features and functionality to test the cameras and display the battery percentage.
UAS-9	**Data Retrieval:** The application should fetch the data and images from the camera trap system wirelessly.	Implement a wireless communication protocol that can retrieve and transmit data over at least 20 meters.
UAS-10	**Efficient data transferal:** The data and images must be accessible to the user at a different time and location.	A download feature will be implemented within the user interface to transfer data and images from the monitoring system to the user's device

Continued on next page

Table 6.2 – continued from previous page

No.	Functional Requirements	Design Specifications
UAS-11	**User-friendly interface:** The user interface should be simple and clear to understand and navigate.	A consistent style shall be followed throughout the interface to promote an intuitive user experience.
UAS-12	**Clear data display:** The user interface shall display retrieved data and images in an organized and understandable format.	Information shall be organised logically and presented in a structured format to aid users in locating and accessing information efficiently.
UAS-13	**Prolonged storage management:** Storage of the data should be managed such that the SD card does not reach capacity.	There will be an option to clear all data off the SD card once the data has been downloaded to the user's device, in order to manage memory efficiently and ensure prolonged system functionality.
UAS-14	**Authentication and Security:** The system should implement authentication and security measures to ensure authorized access.	There will be a network authentication process implemented to provide security to the system.

6.4 Design Choices

6.4.1 Micro-controller

Various micro-controllers were investigated and analysed to determine which was the best fit for this particular system. The analysis shown in Table 6.3 below focuses on three micro-controllers (the Arduino Nano 33 IoT, ESP32-WROOM-32 and Raspberry Pi Zero W), which were chosen due to their suitability to the system as a whole. The table displays the particular features of the micro-controllers that are relevant to the user interface subsystem specifically, namely the processing and memory capabilities and offered connectivity protocols.

After thorough analysis, the ESP32-WROOM-32 and Raspberry Pi Zero W were determined as the best choices for the user interface subsystem as their features best align with the defined user requirements and design specifications. The ESP32-WROOM-32 was ultimately chosen as the final choice, as detailed in the Sensing Section.

The ESP32-WROOM-32's dual-core processor meets the requirement for responsiveness (UAS-6), and its memory capabilities align with data storage needs (UAS-9, UAS-10). Offering WiFi, Bluetooth, and Ethernet connectivity, it caters to accessibility demands (UAS-7) and efficient data transfer (UAS-3, UAS-14).

Table 6.3: Micro-controller Suitability Analysis

Micro-controller	Processor	Memory	Connectivity
Arduino Nano 33 IoT	SAMD21 Cortex processor, 48MHz: provides sufficient processing power for handling user interface tasks efficiently	256KB flash memory, 32KB SRAM: allows for storage of moderate-sized program code and data handling	WiFi and Bluetooth (Nina W102 uBlox module), hardware support for SPI and I2C

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Table 6.3 – continued from previous page

Micro-controller	Processor	Memory	Connectivity
ESP32-WROOM-32	Dual-core Tensilica LX6 processor, 240MHz: provides substantial processing power suitable for efficient simultaneous task handling and demanding user interface applications	448KB ROM, 520KB SRAM: provides sufficient storage for program code and data storage required by the user interface subsystem	Wifi, Bluetooth and Ethernet connectivity
Raspberry Pi Zero W	Broadcom BCM2835, 1GHz ARM11: provides significant processing power for running basic user interface applications	512MB RAM, MicroSD card slot: RAM allows for efficient simultaneous task handling and suitable for applications that don't require extensive memory usage	WiFi and Bluetooth connectivity

6.4.2 Front-end Design

Front-end design is a significant aspect of user interface design. It serves as a bridge between the users and the functionality of the system, and plays an important role in determining the user's experience with the system as a whole. Figure 6.1 below displays the initial front-end design of the user interface, which is a hand-drawn sketch of the user interface pages.

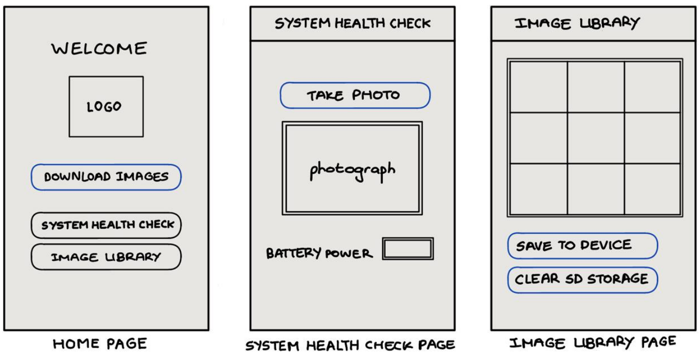

Figure 6.1: Initial Rough Design of Front-end

By referring to Sections 6.2 and 6.3, the front-end was designed with the aim of aligning the features to meet the defined requirements and specifications. Emphasis was placed on making a minimalist design with a user-intuitive flow rather than implementing a design that is more aesthetically inclined.

6.4.3 System Architecture

The system architecture provides an overview of the architectural framework of the user interface design and implementation. It discusses platform choice, communication protocols, developmental environments and data handling implementations, as well as security and authentication protocols specific to the subsystem. Each architectural aspect is designed to ensure intuitive usability, data access and secure interactions, therefore enhancing the overall functionality and effectiveness of the subsystem.

Platform Choice

Various formats are available for the design of a user interface integrated with the ESP32-WROOM-32. A native mobile application on a smartphone or tablet can be designed and implemented to allow the user to view and interact with the data collected. However, the design would have to be tailored specifically to the type of device used. Since the researcher did not state their use or preference of a particular device used to receive the data, designing a mobile application is a limiting design choice.

Cloud Integration is another design option. The ESP32-WROOM-32 can be integrated with cloud services such as AWS IoT, Google Cloud IoT or Azure IoT Hub, where data can be stored, accessed and displayed using cloud-based tools. This, however, is not a viable choice in the scope of this project as these services typically incur costs based on usage and data storage.

The ESP32-WROOM-32 supports web-based applications, where a web server can be created on the module to host a web interface. Users can access this interface through any type of web browser on any device connected to the same network, allowing for remote monitoring and control of the device and its data. This versatility, along with the cost-effectiveness, scalability, ease of development and remote accessibility of web-based applications present them as the best choice for integrating with the ESP32-WROOM-32 for this subsystem. They provide an efficient solution for viewing, interacting with, and managing the collected data across various devices. An asynchronous web server was chosen to handle HTTP requests concurrently and increase the efficiency of the data handling process.

Communication Protocol

The ESP32-WROOM-32 is a very versatile micro-controller; able to communicate via various wireless protocols. For the camera trap system, the ideal communication protocol must be low power (aligning with the power subsystem), able to transmit a substantial amount of data (collected from the sensor subsystem) and have a minimum transmission distance of 20 meters (an approximation based on the height of the Fork-tailed Drongos' nests).

Table 6.4 below displays the capabilities of a few selected communication protocols that were researched [42] in order to determine the best choice for the system.

Wi-Fi was chosen as the communication protocol for the system due to it being the best fit for the necessary requirements mentioned above. There are three client-server communication protocols: HTTP Requests, Server-Sent Events and Websockets. Server-Sent events utilise HTTP connections and the event source protocol to send updates to the client, with the client being unable to send data back. HTTP requests send and receive data with the micro-controller acting an access point, and it aligns with the requirements outlined above. Websockets are also a viable choice, establishing persistent connections between the server and client and facilitating data exchange through TCP connections.

HTTP requests were selected as the client-server communication protocol as they align with the system's requirements and allow for bidirectional communication between the ESP32 and the connected devices. HTTP requests are widely supported and simple to implement, making them a practical choice for this subsystem.

Table 6.4: ESP32 Wireless Communication protocols

Communication protocol	Power Consumption	Transmission Distance Capability	Bandwidth	Additional Features
Bluetooth Low Energy (BLE)	Low	Short	Low	Supports broadcasting and mesh network
Bluetooth Classic	High	Short	Medium	Optimised for continuous data streaming
ESP-NOW	Low	Long	Medium	Fast
Wi-Fi	Low	Long	High	Exchanges data using HTTP requests, Server-Sent Events or Websockets
LoRa	Low	Long	Low	Requires a LoRa transmission chip for use with ESP32

Developmental Environment

The developmental environment encompasses the tools and languages used in the development process of the subsystem. The design choice was made to design the web application in the Arduino IDE using a combination of C++ and JavaScript in conjunction with HTML and CSS. Frameworks such as Django, Flask and Hypertext Preprocessor (PHP) were not selected due to the weight of their tools and memory requirements of their libraries. Using HTML and C++ is not only light in their resource usage, but they also allow for seamless integration with the firmware of the ESP32. Finally, the developer was familiar with HTML and C++ which aided in streamlining the development process.

Data Handling

Data can be retrieved from the Micro-SD card by implementing either the SD.h or SDD_$MCC.h libraries, which use an SPI controller and an ESP32 SD/SDIO/MCC controller respectively. The SD.h library was selected for use in the subsystem due to its lighter weight and more focused design. The subsystem requires basic SD card operations on a standard SD card, therefore the SD.h library is sufficient. The data on the Micro-SD card can also be cleared using this library, effectively clearing the system's storage for the next set of camera trap images to be stored. The data is stored in the Serial Peripheral Interface Flash File System (SPIFFS), allowing it to be retrieved and displayed on the web application. The SPIFFS was selected over other file systems, such as In-Memory Storage and LittleFS, due to its file system operations, integration with web server applications and simple deployment. The data can also be pulled from the SPIFFS and downloaded to the user's device, effectively completing the full data movement.

Security and Authentication

The ESP32 is being set as an access point to enable Wi-Fi connection, which means that it will have its own Wi-Fi network that nearby devices can connect to. The SSID and password of this network can be set by the developer and made known to the users only: effectively securing access to the web application and data. After the user has logged onto the network for the first time, they will not be required to put in the password for subsequent sign-ins.

6.5 Final Design

This section details the final front-end and back-end design of the subsystem and explains how the designs are integrated with one another and with the camera trap system as a whole.

6.5.1 Front-end

HTML and CSS are embedded within the C++ code as strings to generate the web pages dynamically and set their style. Figure 6.2 below shows the code used to generate the home page of the web application. *getHomePageContent* is a Java method which returns a string containing the HTML code, which represents the structure and content of the page. The style of the web page is saved in a separate CSS file which is linked in the <head> section of the HTML code. The other two web pages are designed with the same structure.

```
String getHomePageContent() {
    String html = """
        <!DOCTYPE html>
        <html>
        <head>
            <meta name = "viewport" content = "width=device-width, initial-scale = 1.0, user-scalable = no">
            <title>Welcome</title>
            <link rel = "stylesheet" type = "text/css" href = "homeStyle.css">
        </head>
        <body>
            <h1>Welcome</h1>
            <img src = "logo.png" alt = "Logo">
            <p>Select an option below:</p>
            <a class = "download-button" href = "/download">Download Images</a>
            <a class = "sensorpage-button" href = "/sensor">System Health Check</a>
            <a class = "librarypage-button" href = "/library">Image Library</a>
        </body>
        </html>
        """;

    return html;
}
```

Figure 6.2: HTML Code for Home Page

6.5.2 Back-end

The back-end of the subsystem consists of configuring the ESP32 as a Wi-Fi access point, establishing communication between the server and client, and setting up the data handling operations. C++ utilizes the various available libraries to implement the web server, handle asynchronous requests and interact with the file system, while HTML and CSS are embedded within the C++ code as strings to generate web pages dynamically.

Appendix D shows the declaration of the access point's credentials and the assignment of a static IP address, as well as the setup of the asynchronous web server. The initialisation of the serial communication, access point set-up and mounting of the SPIFFS file system is also displayed, as well as the beginning of the definitions of HTTP routes and request handlers.

The data consists of captured images that are stored on an external SD card that acts as the data storage of the camera trap system. The SD.h library and documentation is used in conjunction with SPI to facilitate communication between the ESP32 and the Micro-SD card, fetching the data from the Micro-SD card. The retrieved data is stored in the SPIFFS file system, before it is served by the web server. HTTP requests are utilized for client-server communication, allowing the ESP32 to serve web pages and respond to requests from connected devices. HTTP endpoint are created on the web server that serves the images to the client when requested (when the 'Download Images' button is clicked). The code for these functions can be found in the Github linked in Section 8.2.

6.5.3 Integration Layer

The final integrated user interface subsystem is shown in Figure 6.3. The front-end and back-end designs are brought together to form a web application with data handling functionality.

The interactive elements implemented in the front-end design of the user interface trigger specific events that call various methods employed in the back-end system. Data is then transmitted from the front-end interface to the back-end server for processing. This communication process involves sending HTTP requests, receiving responses, and updating the user interface accordingly to reflect the outcome of the operation.

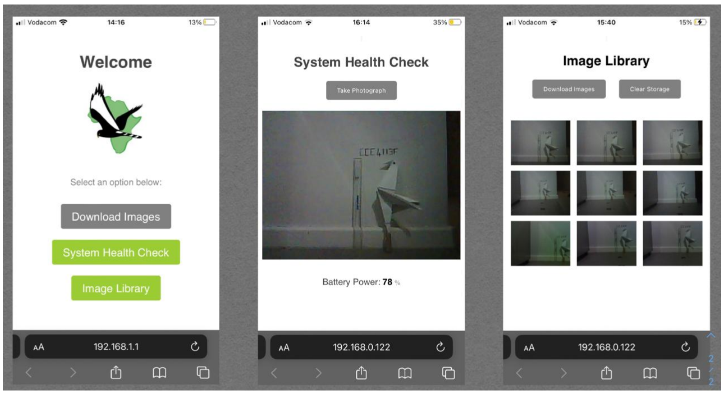

Figure 6.3: Final User Interface Design

6.6 Testing and Results

Testing is an important step that occurs near the end of the design process, offering insights into the performance and user experience of the subsystem and validating its functionality and efficiency. This section presents the results of four key assessments with the goal of evaluating these results to highlight possible future areas of improvement.

6.6.1 Network Speed Test

This test was conducted to determine how quickly the web server and application starts up and responds to user requests. Web developer tools were used in this test, and the results can be seen in Figure 6.4 below. The test is run multiple times, and each time it is observed that the web server sets up in approximately under one hundred milliseconds.

However, there are errors when attempting to start up the web application with a significantly larger number of images. This poses a problem as the camera trap system will need to save a large quantities of images to the file server at a time.

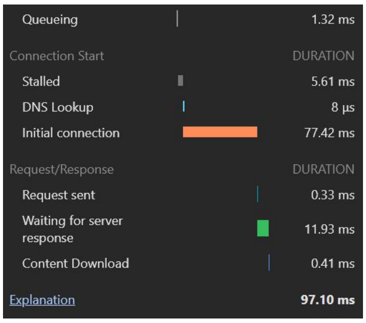

Figure 6.4: Network Speed Test Results

6.6.2 Data Transfer Test

The data transfer test involved retrieving images from the file server and populating the web application. This test was successful, proved by the visibly populated images on the web application as well as the developer tools (displayed in Figure 6.5 below).

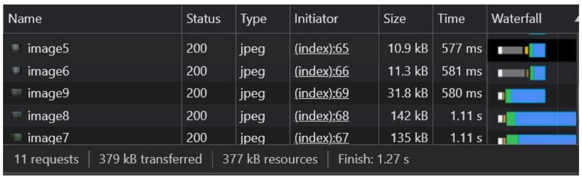

Figure 6.5: Data Transferal Test Results

6.6.3 Accessibility Test

Figure 6.3 shows screenshots of the web application running on Safari on a mobile device. The web application was also run on Google Chrome and Mozilla Firefox on a laptop and tablet to test the application's adaptability to different types of browsers and devices, with positive results for each browser and device type. The stylistic design of the pages ensure that the content is always centered to the device's screen size and orientation.

6.6.4 Usability Survey

A usability survey (which can be seen in Appendix E) was conducted to evaluate and determine the overall usability of the web application. By collecting feedback, we can identify and isolate areas of improvement and implement iterative design to enhance usability and user satisfaction.

The usability survey consisted of a simple google form with five questions that the respondents completed after viewing and navigating through the web application. The respondents consisted of a selection of ten random people that were asked to participate, and the questions were designed with the user requirements in mind. The results of the survey displayed that the respondents found the web application easy to navigate and user friendly, with an highly-rated overall usability of 8.8/10. However, it was also discovered that the respondents found that the application sometimes responded slowly to their requests.

6.6.5 Acceptance Test Procedures Analysis

Acceptance Test Procedures (ATPs) are derived from the subsystem requirements and are used to test the subsystem's performance and determine if its objectives have been met. For this user interface subsystem, User Acceptance Testing (UAT) was chosen to be implemented and the results are displayed in Table 6.5 below.

Table 6.6: Acceptance Test Procedures and Results

No.	Test Description	Acceptance Criteria	Test Result
UAT-1	Usability	The interface should be designed such that it is easy to navigate and understand.	**Passed:** The user interface was rated an 8.8/10 in the usability survey.
UAT-2	Data Retrieval	Data retrieval should be conducted in a way that avoids disturbances to the birds' nests, enhancing ease of use and reducing the need for the researcher to climb the tree to retrieve the data manually.	**Passed:** The data can be successfully retrieved wirelessly via Wi-Fi HTTP protocols from a maximum distance of approximately 50 meters.
UAT-3	Data Transferal	Since the images will be analyzed at different times and locations, the user application must have an option to download the images onto the user's device.	**Passed:** The user can download the jpeg images from the web application to their device.
UAT-4	Data Storage	The user interface should have some feature to clear the data off of the physical camera trap after it has been retrieved, in order to free up memory.	**Failed:** There is implemented functionality to clear the data off the SD card after it has been retrieved, but it is not always successful with larger data groups.
UAT-5	Data Display	The retrieved data and images should be displayed in an organized and understandable format on the web interface.	**Passed:** The usability survey indicated a rating of 4.7/5 for the data display.
UAT-6	Real-time responsiveness	The interface should respond to user interactions and data requests within 5 seconds.	**Failed:** The system does not always respond promptly and occasionally requires more than 5 seconds to respond to requests.
UAT-7	Accessibility across devices	The user interface should be accessible from various types of devices.	**Passed:** As seen in the accessibility test, the web application is accessible across all devices and browsers.
UAT-8	System Health	The designed architecture must include features for observing the health of the other subsystems.	**Passed:** There is functionality for taking a test image on the camera and the battery health is displayed.

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Table 6.6 – continued from previous page

No.	Test Description	Acceptance Criteria	Test Result
UAT-14	Authentication and Security	The system should implement authentication and security measures to ensure authorized access.	**Passed:** The Wi-Fi network requires credentials in order to be accessed, and the IP address of the web application must also be known in order to view it.

The majority of the ATPs were met, indicating relatively successful adherence to the specified requirements and objectives of the user interface subsystem.

Data Storage (UAS-4) and Real-time Responsiveness (UAS-6) did not pass. In Data Storage, the system occasionally fails to clear data from the camera trap's SD card effectively, potentially due to memory constraints or algorithm inefficiencies. This issue can disrupt system performance, particularly when dealing with larger datasets. Similarly, Real-time Responsiveness problems may arise from software inefficiencies or network congestion, causing delays in user interactions and data requests. To overcome these challenges, improvements in algorithm efficiency, error handling, and network optimization are essential to ensure smoother system operation and better response times.

Other aspects of the system, such as Usability (UAS-1) and Data Retrieval (UAS-2), performed well. The user interface received high usability ratings, indicating ease of navigation and understanding for users. Additionally, data retrieval methods via Wi-Fi HTTP protocols proved successful, minimizing disturbances to bird nests during data collection. These successes highlight the system's potential and effectiveness in meeting user requirements and objectives.

Moving forward, by addressing the identified failures and prioritising implementing improvements the system can better fulfill user needs and expectations while delivering a seamless and efficient user experience.

6.7 Conclusion

In conclusion, the user interface subsystem successfully bridges the gap between the camera trap system and the researcher. Through requirements analysis and iterative design, a user-centric interface that meets the diverse needs of researchers like Ben Murphy has been created .

The subsystem relies on a web-based application architecture to facilitate remote access and seamless data management across devices. Leveraging the ESP32-WROOM-32 micro-controller's web-server capabilities, emphasis was placed on simplicity and functionality in the front-end design, resulting in a minimalist interface.

The choice of Wi-Fi communication, enabled by HTTP requests, ensures low power consumption, long-range connectivity, and compatibility with the ESP32-WROOM-32. Incorporating lightweight resource usage and seamless integration with micro-controller firmware, a user-friendly and efficient interface was developed. Additionally, a credential-based authorisation has been implemented for access to the web application.

Through extensive testing and validation, the user interface subsystem has proven to be reliable, efficient, and secure, catering to the specific needs of ornithologists. This subsystem ensures uninterrupted operation and seamless data collection, empowering researchers to monitor the fork-tailed drongo effectively in various field conditions.

Chapter 7

Physical Enclosure (KRNNEN001)

7.1 Introduction

This section pertains to the physical enclosure for the camera trap system. The physical enclosure is the housing in which the ESP32, the sensors,power system and all other components that make up the camera trap system will be. The physical enclosure is meant to rest on a branch 1 m from the nest of the fork tailed drongo. The physical enclosure is responsible for ensuring that the camera trap system operates in the harsh conditions of the Kalahari desert by employing cooling mechanisms and protection from environmental elements that have the potential to make the system malfunction. Furthermore, the physical enclosure must provide the sensors with their optimum placements for a streamlined operation of the system.

This section details the design considerations, design process, simulations and testing procedures that were used to develop and evalute the effectiveness of the physical enclosure subsystem.

7.2 Requirements

Following the stakeholder engagement process, a list of high level user requirements for the physical enclosure subsystem were derived. The user requirements were then analysed and a list of functional requirements were derived. The main concerns of the user in the physical enclosure subsystem were cooling, stability, robustness, longevity and not invasive to the surrounding environment. The specifications and requirements were then used in the design process to produce a final design that met them. The user requirements and functional requirements are shown in table 7.1 below.

Table 7.1: User Requirements and Functional Requirements for the Physical Enclosure Subsystem

User Requirements	Functional Requirements
Mountability: The enclosure of the system must be mounted on a branch	**Mechanical Stability:** Incorporate a fastening mechanism to secure the enclosure to a surface.
Ease of access: The enclosure should allow for the device to be easily removed for maintenance	**Detachable Face:** Incorporate a detachable face into the design to allow for east removal of the system.
Robust Design: The enclosure should be made such that the system operates in the rain and dust.	**Sealed Enclosure:** The interior of the enclosure should have no openings or gaps. Additionally, the material used must not react with water.
	Continued on next page

Non-invasive: The enclosure of the system should blend in naturally	**Natural Material:** The enclosure should be constructed out of a material that occurs in nature.
Portability: The enclosure should be able to be moved around.	**Lightweight Design:** The enclosure should not weigh more than 3kg.
Security: The system should be secured inside the enclosure.	**Locking mechanism:** The enclosure should incorporate a locking mechanism to prevent unauthorised access.
Low cost of system: The system as a whole should be designed to have a low cost.	**Cost Effective Enclosure:** The enclosure should cost less than R500.
Monitoring: The camera trap should be placed in the enclosure such that its view is not obscured.	**Sensor Placement:** The enclosure should not obscure the view of the camera trap. Additionally, the light sensor should have an unobstructed view of the external light conditions.
	Temperature Reduction: The enclosure should maintain the internal temperature to less than 40 °C at an external temperature of 50 °C.
	Solar Panel: The top face must have minimum dimensions of 112mm by 168mm

7.3 Possible Implementations

In order to achieve the requirements of the subsystem the design process was broken down into three sections, namely: the geometry, material used to build the enclosure, and cooling mechanism used.

7.3.1 Geometry

When looking at possible implementations of the geometry, the stability and suitability of each geometry was evaluated and the one that was most suitable to meet the functional requirements was selected.

Spherical Geometry

The first geometry considered is a spherical enclosure with a hollow interior within which the camera trap system is to be placed. A challenge with the spherical geometry is that it does not have any flat surfaces, and therefore it is highly likely to roll off the branch which it is placed on. Additionally, another drawback to the absence of flat surfaces is the difficulty of mounting the solar panels on it.

Triangular Geometry

The second geometry considered was a triangular enclosure with a hollow interior where the camera trap system is to be placed. Although the triangular geometry is an improvement on the circular one due to it having flat faces which can rest on a branch, the challenge of mounting the solar panels on it still persist.

Cubic Geometry

The third geometry considered was a cube with a hollow interior where the camera trap is to be placed. The cube has all flat faces, meaning it can rest both on the tree branch as well as a solar panel mounted on it easily.

7.3.2 Material

The project is being carried out in the Kalahari desert which experiences extremely high temperatures which are worsening due to climate change [43].The material of choice must be able to withstand the harsh climate, as well as providing waterproofing to prevent the camera trap system being destroyed. Additionally, the material should provide some manner of insulation to maintain the internal temperature of the enclosure within the threshold of operation of the camera trap system. Furthermore, the material of choice should be non-invasive.

Metal

The first material considered for the physical enclosure was metal. Metals are waterproof although, they are reactive with water [44]. A simple method of preventing corrosion of the metals is by painting the metal. Metals also have an extremely high melting point which will ensure they do not melt in the extreme Kalahari climate [45]. Due to their internal structure, metals are have a high thermal conductivity leading to an increased chance of damaging the components of the camera trap system by having the interior of the enclosure above the temperature threshold [45]. Furthermore, another drawback to using metal is that it will be invasive to the environment of the drongos.

Wood

Owing to the its chemical composition, wood does not melt, but rather combusts at extremely high temperatures, surpassing those encountered in the Kalahari by far [46]. Furthermore, due to its chemical structure wood demonstrates insulative properties [46]. Wood is inert meaning it does not react with water or other atmospheric elements. Moreover, it is non-invasive to the environment of the fork tailed drongos. However,a downside to using wood pertains to its propensity to absorb water, leading to rotting and necessitating frequent replacement of the enclosure.

Epoxy Coated Wood

Applying a layer of epoxy onto the wooden surfaces is a simple and effective way of preventing water absorption, preventing rot as mentioned above. The epoxy coating does not affect the other properties of wood mentioned above.

7.3.3 Cooling mechanism

The harsh climate of the Kalahari requires the enclosure to employ a cooling mechanism to effectively maintain the internal temperature of the enclosure below the maximum operation threshold of the camera trap systems components. Furthermore, the cooling mechanism of the enclosure should consume minimal to no power in order to extend the battery life of the system.

Thermoelectric Cooling

Thermoelectric electric devices achieve cooling by using electricity to pump out heat through the Peltier effect [47].It is an effective method of reducing the temperature within the enclosure. A drawback of using thermoelectric cooling is it shortens the lifespan of the battery due to its power consumption.

Cooling fan

A fan installed in the enclosure would cool the enclosure by increasing the airflow inside. A drawback of using a fan as a cooling method is that it requires power from the battery, shortening the lifespan.

Holes

An alternative cooling approach involves the introduction of multiple perforations on the surface of the enclosure. This technique cools the interior of the enclosure by increasing the airflow, without the use of active power. A drawback of using this technique is that it exposes the interior of the enclosure to the elements of the Kalahari that could potentially damage the camera trap system, such as dust and rain.

Air Gap

The introduction of a layer of air would retard the flow of heat into the enclosure due to the insulating nature of air [48]. This would lead to a lower internal temperature of the enclosure. The use of an air gap does not require any active power, and therefore does not affect the lifespan of the battery.It also does not expose the interior of the enclosure to external interference, while effectively lowering the internal temperature of the enclosure.

7.4 Design Process and Decisions

In terms of the geometry, the spherical implementation is not ideal because of its lack of flat surfaces, making it difficult to both mount on a branch as well as to mount the solar panel on. The triangular enclosure would be an improvement as it has flat surfaces on which it can rest on the branch, but the challenge of mounting the solar panel on the top face still persists. The cubic implementation is both easily mountable and the solar panel will rest comfortably on its top face. Therefore, the geometry of choice for the enclosure is the cubic geometry.

In terms of the material of choice of the enclosure, metal is not a good choice owing to the fact that it is a thermal conductor, which will increase the risk of the internal temperature exceeding the threshold of operation of the camera trap system. A wooden enclosure would be ideal, except for the fact that it absorbs water, leading to rot and therefore will require frequent replacement. Coating the wood with a layer of epoxy provides a simple and effective solution to this challenge. Therefore, the material of choice for the enclosure is wood coated with a layer of epoxy. The specific wood being used is plywood due to it being lightweight, strong and cheap [49].

In terms of the cooling mechanism, both thermoelectric cooling and a cooling fan are both effective ways of reducing the temperature of the interior of the enclosure, but they require power which ultimately leads to the battery having to be charged more frequently. Making holes on the faces increases the airflow inside the enclosure, but ultimately exposes the interior of the enclosure to dust and rain which can damage the camera trap system. The use of an air gap introduces an extra layer of insulation, preventing the external heat getting into the enclosure. Furthermore, the use of an air gap does not expose the interior of the enclosure to the environmental elements, and also does not require any power. Therefore, the cooling mechanism of choice is an air gap.

The solar panels should be placed so that they receive the optimum sunlight, for the best performance. This placement is on the top face of the box. There are two solar panels, each with dimensions of 112mm by 84mm. Therefore, the minimum dimensions of the top face are 112mm by 168mm to accommodate both solar panels placed side to side.

The enclosure must have a large enough gap such that it does not obscure the view of the camera. For re usability, the opening for the camera was designed to accommodate other cameras in addition to the ESP32-Cam and the ArduCam SPI mega, which are used in the current implementation of the camera trap system. To achieve this, a semi-circular cut of radius 35mm was made on the bottom of the front face. The cut is to be covered by a semi-circular glass pane of radius 35mm and thickness 5mm to prevent ingress of dust.

The enclosure will have a detachable back door to allow for the removal of the system in case maintenance is required. To prevent unauthorised access to the camera trap system, both the door and the enclosure will have a simple locking mechanism which will have a hole of radius 12mm to allow for a padlock to be inserted for locking.

Additionally the enclosure should have an allowance for the ambient light sensor to sense the external light conditions, from the interior of the enclosure. To achieve this, a cutting of 50 mm by 50 mm is made into the top face. This opening will be covered by a 50mm by 50mm glass pane of thickness 5mm to protect the interior of the enclosure from external elements.

7.4.1 Simulations

Simulations were ran on SolidWorks to determine the optimal dimensions, which include the height of the air gap, thickness of the wood, and height of the enclosure necessary to achieve the temperature requirement. The decision to opt for simulation over physical testing made because it was impractical and expensive to build each iteration to be tested individually. SolidWorks was used because it is a well established software in which simulations on a model can be ran, and accurate results produced. It is acknowledged that while SolidWorks serves as a valuable simulation tool, its outputs do not offer a definitive guarantee of replicability in practical implementation.

All the simulations were ran at an external temperature of 50 °C, which is a temperature higher than the maximum temperature of the Kahalari [43]. This is to ensure that if an extremity is reached, the system will still operate. All the readings from the simulations were recorded and subsequently graphs were sketched from the results. The results shown below are under the condition that all parameters, except the one under investigation, remain consistent with those in the final design . The findings from the all other iterations are omitted from the report as they are deemed non pertinent.

Height of Air Gap

The air gap serves as the main cooling mechanism of the enclosure. In order to meet the requirement that the internal temperature of the enclosure must not exceed 40 °C, the air gap must be made sufficient large to achieve this. The simulation was performed by increasing the height of the air gap from 0 mm (i.e no air gap) to 40 mm in incremental increases of 5mm for each successive iteration. The results from the simulation are shown in figure 7.1 below.

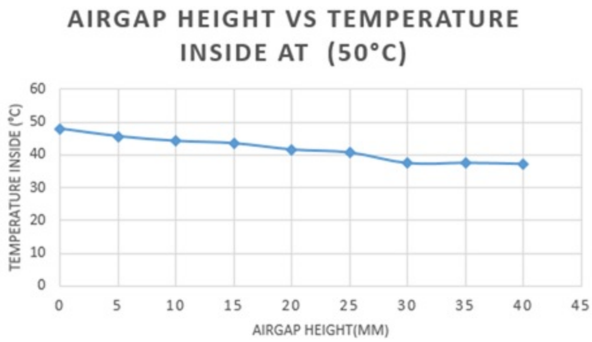


Figure 7.1: Effect of varying air gap on internal temperature

The results from the simulation show that initially, as the height of the air gap is increased, there is a sharp decrease in the internal temperature of the enclosure. Beyond an air gap of 30 mm, the impact of enlarging the air gap diminishes.

The temperature when the air gap is at 30 mm is 37.5 °C, which is within the requirement that the interior of the box should not exceed 40 °C. At this temperature, there exists a margin to accommodate higher external temperatures attributable to climate change. Therefore, the chosen height of the air gap is 30 mm.

Height of the Enclosure

As the height of the enclosure is increased, the cooling effect due to convection currents increases [50]. From the previous section, the minimum height of the box must be 70 mm to make a large enough cut to prevent the field of view of the camera trap being obscured.

The simulation was performed by increasing the height of the box from 70mm to 120mm in incremental increases of 10mm for each successive iteration. The results from the simulation are show in figure 7.2 below.

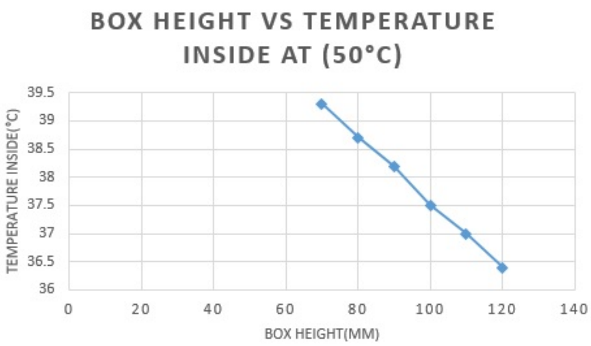


Figure 7.2: Effect of varying height of the enclosure on internal temperature

The results from the simulation show that the internal temperature decreases when the height of the enclosure increases. The chosen height of the enclosure is 100mm. This is because as the height of the enclosure increases, the center of gravity becomes higher, making the enclosure more unstable. The cost of the enclosure also increases because more material is being used to construct the enclosure. The height of 100mm is suitable because the temperature of operation at this height is 37.5 °C, which is well below 40 °C, and therefore is a suitable compromise between cost, internal temperature and stability.

Thickness of the wood

The wood needs to be thick enough to serve two purposes, namely: insulation and support. This simulation will be done in two parts. The first is to measure the effect of varying the thickness of the wood on the temperature, and the second is to establish whether the wood will be able to support an applied load at the selected thickness.

The first part of the simulation was done by increasing the thickness of the wood from 2.5 mm to 22.5 mm in incremental increases of 2.5 mm for each successive iteration, and measuring the internal temperature. The results from the simulation are shown in figure 7.3 below.

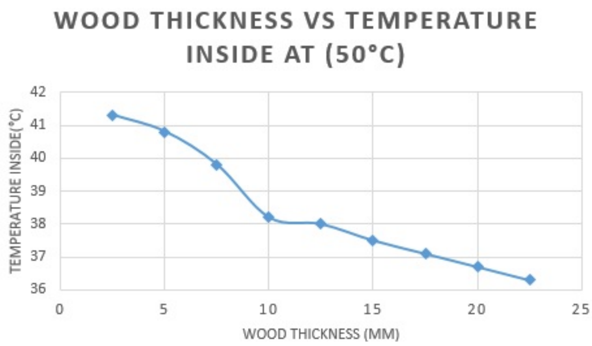


Figure 7.3: Effect of varying thickness of the wood on internal temperature

The results from the simulation confirmed that as the thickness of the wood was increased, the internal temperature of the enclosure decreased. Due to the increasing cost of the wood as the thickness increases, it was decided that a sensible thickness of choice was 15mm, which had an internal temperature of 37.5 °C.

The second part of the simulation was done by applying a load of 5 kg, which is the same as a heavy bird, to the top face of the enclosure, and measuring the deflection due to the load. The results from the simulation are shown in figure 7.4 below.

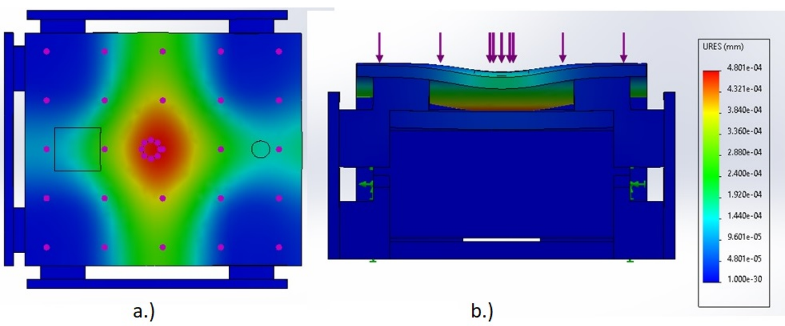


Figure 7.4: Deflection due to load a.)Top view b.)Side view

The deflection simulation showed that the maximum deflection when a load was a applied was $4.8 * 10^{-4}$mm and it occurred at the center of the top face. This is because there is no support in the middle of the top face.

This deflection is negligible. Therefore, a thickness of 15mm is to be used as it is a suitable compromise between strength, cost and internal temperature.

7.5 Final Design

The dimensions, material, geometry and design of the enclosure were designed to meet the user and functional requirements. This section provides a summary of the final design, which is a result of the design process described in the previous sections.

The enclosure is to be constructed from epoxy painted plywood, and will have a height of 100 mm, and cross sectional dimensions of 200 mm by 250 mm. Additionally, there will be an air gap of 30 mm on all faces except the bottom face and the back face. The air gap is to be made by having supports of 50 mm by 50 mm and height 30 mm on the corners of the exterior of the face which serve as a foundation for a second plank of wood to be attached to.

The front face will have a semi circular cutout of radius 35 mm to enable the camera trap to have a view of the fork tailed drongos. This will be covered by a semi circular glass pane of radius 35 mm and thickness 5 mm to prevent disturbance of the camera trap system by the external environment. The top face will have a 50 mm by 50 mm cutout to enable the ambient light sensor to accurately measure the external light levels. There will also be glass pane covering of 50 mm by 50 mm and thickness 5mm on this to prevent external disturbances to the system. Additionally, there will be two holes in the top face of radius 20 mm to allow the wires from the solar panels that will rest on it to reach the charging system. On each side face, there will be two holes of radius 7.5 mm, to enable a rope to be passed through and fastened to the branch for additional stability. The drawing of the final design is shown below in figure 7.5.

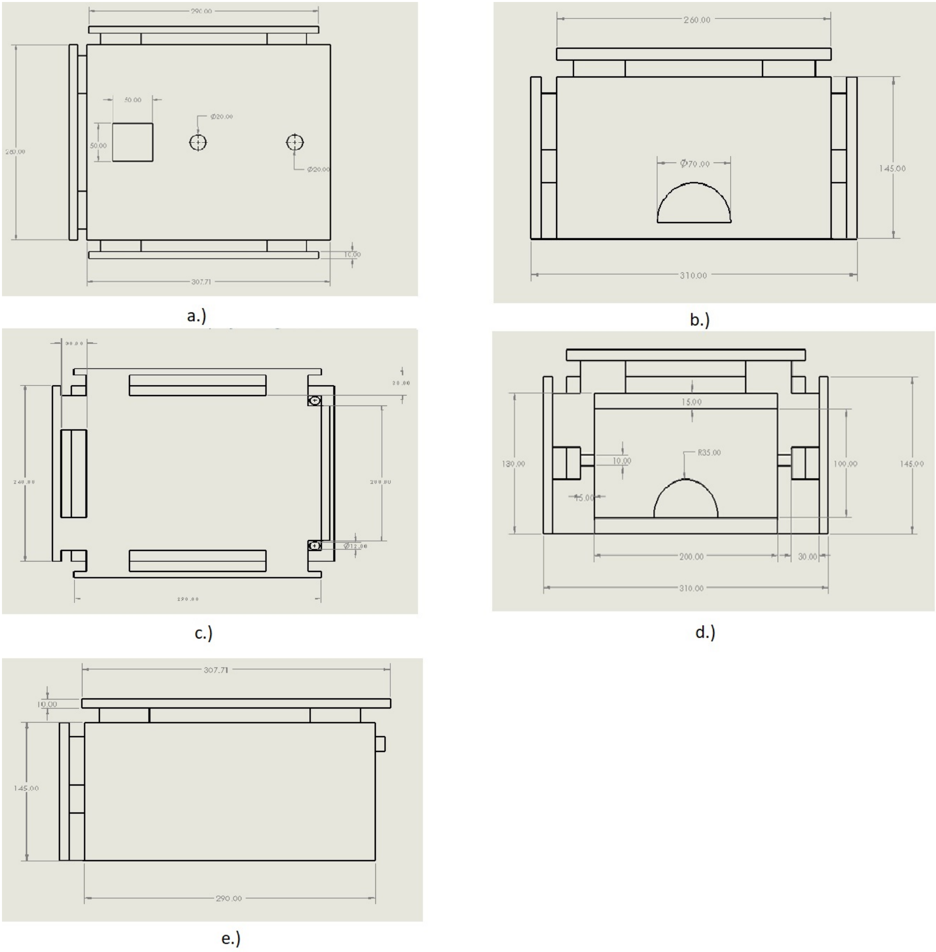


Figure 7.5: Drawings of final Design of the enclosure a.)Top view b.)Front view c.)Bottom view d.)Back view e.)Side view

The back face will have a detachable door to enable the system to be removed for maintenance. This detachable back door will have a locking mechanism to prevent unauthorised access to the enclosure. The drawings of the design for the detachable door is shown below in figure 7.6.

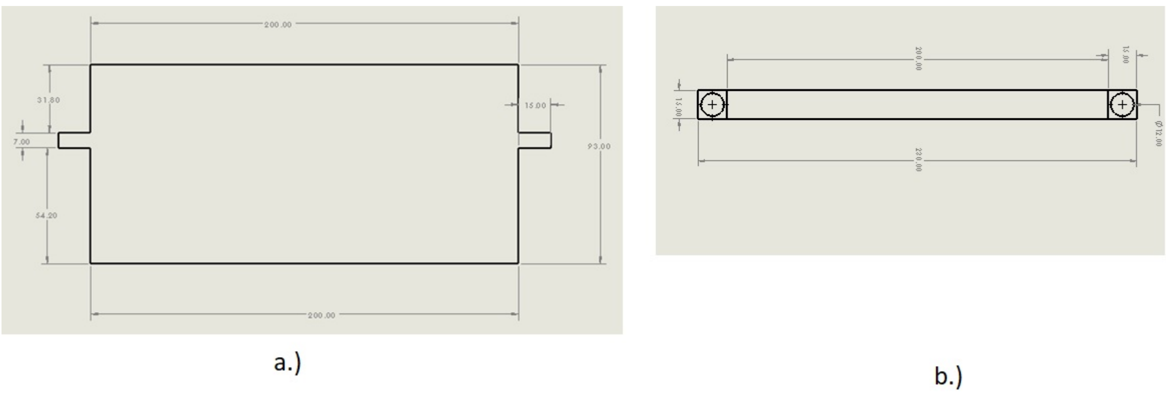
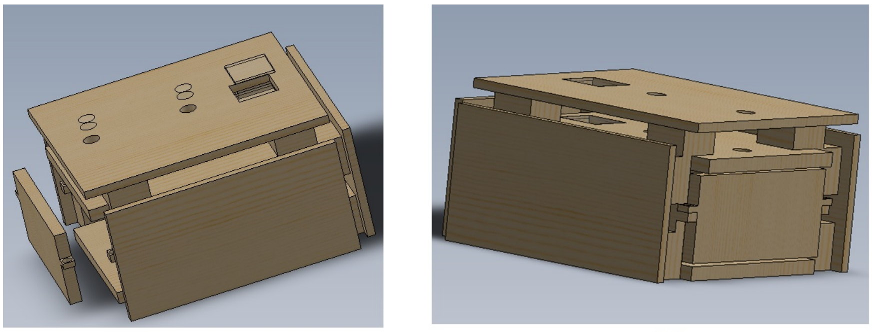


Figure 7.6: Drawings of final Design of the detachable door a.)Side view b.)Top view

The model of the final design of the enclosure is shown below in figure 7.7.



a.) b.)

Figure 7.7: Model of the enclosure a.)Deconstructed view b.)Fully constructed view

7.6 Acceptance Test Procedures

After the definition of the functional requirements, a set of Acceptable Test Procedures were developed in parallel with the rest of the subsystem design. The ATPs provide detailed procedures to determine whether each of the requirements was met.

Table 7.2: Acceptance Test Procedures and Results

No.	Test Description	Acceptance Criteria	Test Result
PES-1	Place all the components into the enclosure.	Components can enter the enclosure unobstructed and fit inside	**Passed.**
PES-2	Tape paper on all interior faces and splash water on all external faces.	Paper comes out dry.	**Passed.**
PES-3	Place enclosure in 50 °C environment and measure the interior temperature after an hour.	The interior temperature should be below 40 °C.	Not possible to perform in Cape Town. Test was passed in simulation.
PES-4	Place enclosure 1m from object. Place camera where system camera is to be placed and take picture.	Object should be unobstructed in resulting picture.	**Passed.**
			Continued on next page

Table 7.2 – continued from previous page

No.	Test Description	Acceptance Criteria	Test Result
PES-5	Construct circuit of an LDR in series with a resistor. Place the circuit where the ambient light sensor is meant to be placed. Vary the external light levels and measure the current of the circuit.	Current is higher when there is more light outside.	**Passed.**
PES-6	Place 5kg weight on the center of the top face for 1 hour and inspect afterwards.	Enclosure shows no evidence of deformity or damage.	**Passed.**
PES-7	Place the enclosure on a 5cm width surface and push slightly.	Enclosure remains on surface.	**Failed:** Enclosure balanced initially but fell off after push.
PES-8	Measure the weight of the enclosure.	The measured weight of the enclosure should be less than 3kg.	**Passed.**
PES-9	Measure the top face.	Top face must have minimum dimensions of 112mm by 168 mm.	**Passed.**
PES-10	Fasten the enclosure onto a surface with a rope.	Rope is able to fit through prescribed openings and fasten the enclosure to the surface	**Passed.**
PES-11	Place the detachable back door in place and lock with 2 padlocks	Back door remains in place, and cannot be removed when padlocks are in place	**Passed.**
PES-11	Compile a Bill of Materials of the total cost of materials used to construct enclosure.	Total cost does not exceed R500.	**Passed.**
PES-12	Drop a 5kg weight on the center of the top face of enclosure from a height of 20cm to 160cm incrementing the height by 20cm each time.	Enclosure shows no sign of damage or deformity.	**Failed:** The enclosure broke into multiple pieces when the weight was dropped at a height of 100cm.

7.7 Testing and Recommendations

A prototype of enclosure was constructed with the dimensions specified in section 7.5. The prototype was put through a series of tests documented in section 7.6 to establish whether the functional requirements were met. This section will discuss the key results as well as provide recommendations for further improvements.

Successful completion of test PES-2 qualifies the enclosure for attainment of an Ingress Protection (IP) rating [51]. The enclosure was awarded an IP rating of IP64 (see Appendix D). This signifies that the enclosure demonstrates resistance to dust ingress and is impervious to water splashing from all directions.

Test PES-3 was not possible to carry out because Cape Town does not get to the extreme temperatures that the Kalahari does as was highlighted in table 7.2. The simulation was performed in SolidWorks and showed an internal temperature of 37.5 °C, which did meet the acceptance criteria.

Test PES-7 failed because the mechanism of fastening the enclosure onto the surface was not effective enough to secure it when an external force was applied. In future, a more effective method of fastening it to the tree branch, such as nailing the bottom face of the enclosure onto the surface can be implemented.

Test PES-12 was performed after all the other tests had been done. The purpose of the test was to investigate the behaviour of the enclosure in atypical conditions such as a tree branch falling on it. The result of test PE-12 shows that the enclosure should be reinforced through methods such as adding internal supports in future to ensure that it does not break in such conditions. The prototype passed all other ATPs.

7.8 Conclusion

The purpose of the physical enclosure subsystem was to provide a suitable housing for the ESP32, the sensing modules, the power system and all other components that made up the camera trap system for the fork tailed drongos.

The enclosure provided a cooling mechanism to ensure the operation of the camera trap system in the harsh climate of the Kalahari. Furthermore, the enclosure was designed with the optimum positioning of each of the sensing modules. It also provided a mechanism to access the system for maintenance.

The final design was obtained from a series of simulations to achieve a final design which was an optimum compromise between performance and cost. A prototype of the enclosure was constructed from the dimensions given in the final design, and the prototype was ran thorough a testing process to confirm whether the final design met the requirements.

From the tests carried out, the physical enclosure was awarded an IP rating of IP64 meaning the enclosure demonstrates resistance to dust ingress and is impervious to water splashing from all directions.

Chapter 8

Conclusions and Recommendations

In conclusion, the final designed camera trap system effectively tackles the problem statement and meets the majority of the user requirements. By addressing the inefficiencies of existing monitoring methods for the Fork-tailed Drongo, the system aimed to provide ornithologists with a reliable, efficient system to improve their experience studying and analysing the avian species.

Through a thorough analysis of the problem and its scope, this report has outlined the design process for each subsystem of the camera trap system. From power management to user interface design, each component has been carefully considered and developed to meet the specific requirements of monitoring the Fork-tailed Drongo in its natural habitat.

Furthermore, the literature review conducted in Chapter 3 has provided valuable insights into key topics such as the Kalahari ecosystem, avian behavior, and technological advancements in camera trap technology. By leveraging this knowledge, the project has been able to design a solution that not only meets the needs of researchers but also respects the limitations imposed by the environment and available resources.

The implementation of this camera trap system offers numerous benefits, including real-time data collection, reduced maintenance requirements, and improved reliability during critical observation periods. Moreover, the use of infrared technology ensures that bird activity can be monitored accurately, even during night-time hours.

It is essential to acknowledge the limitations of this project, such as budget constraints, component availability and testing limitations. By documenting the design process and test results thoroughly, this report provides a solid foundation for future iterations of the system.

Various improvements were suggested in the respective subsystems sections. The power subsystem explored the implementation of an automatic disconnection of power, while changing the type of PIR sensor was suggested to improve the average trigger speed in the sensing subsystem. Data storage and real-time responsiveness issues in the user interface subsystem caused delays in user interactions and data requests, which can be managed with network optimisation practices and improving algorithm efficiency. Finally, the hardware subsystem explored improving the fastening mechanism of the enclosure to provide security against external forces.

In summary, the development of the redesigned camera trap system combines engineering design with ecological knowledge, demonstrating the potential for technology to enhance the process of studying avian species.

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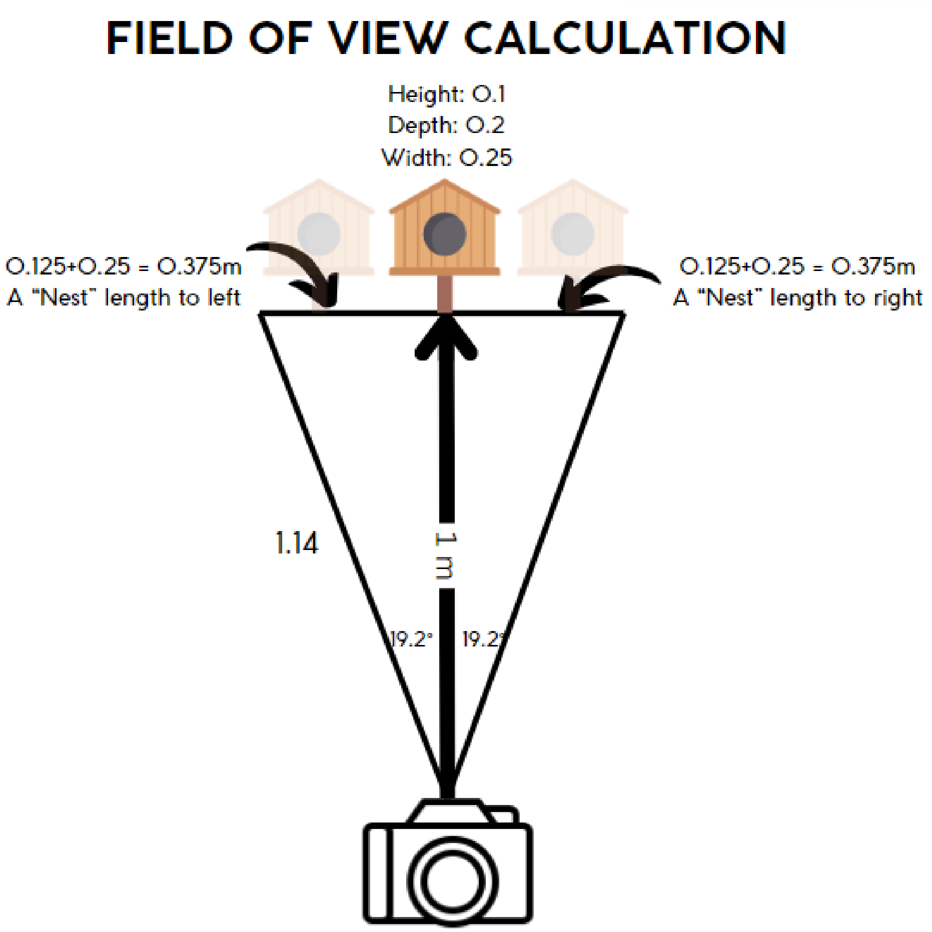
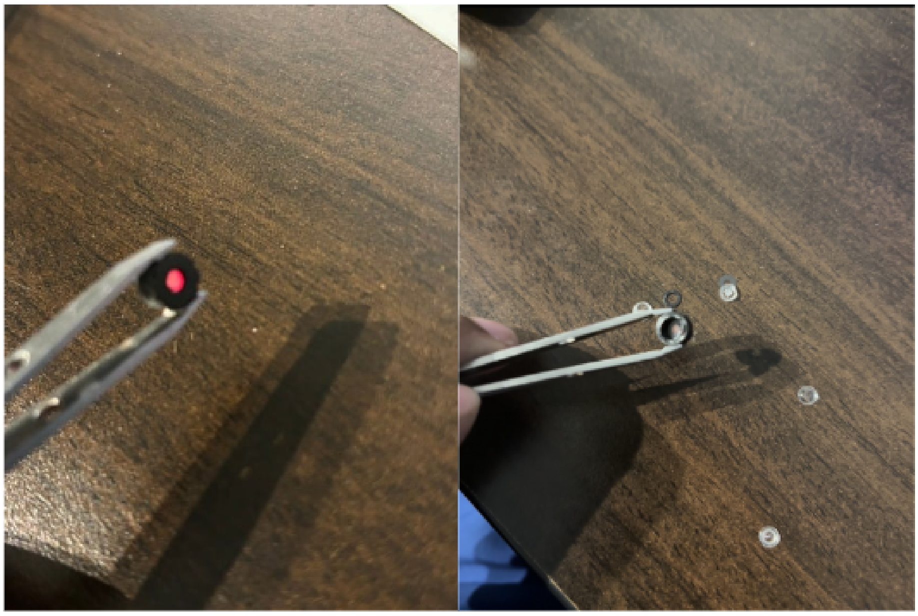
Appendix A

Minimum FOV calculation



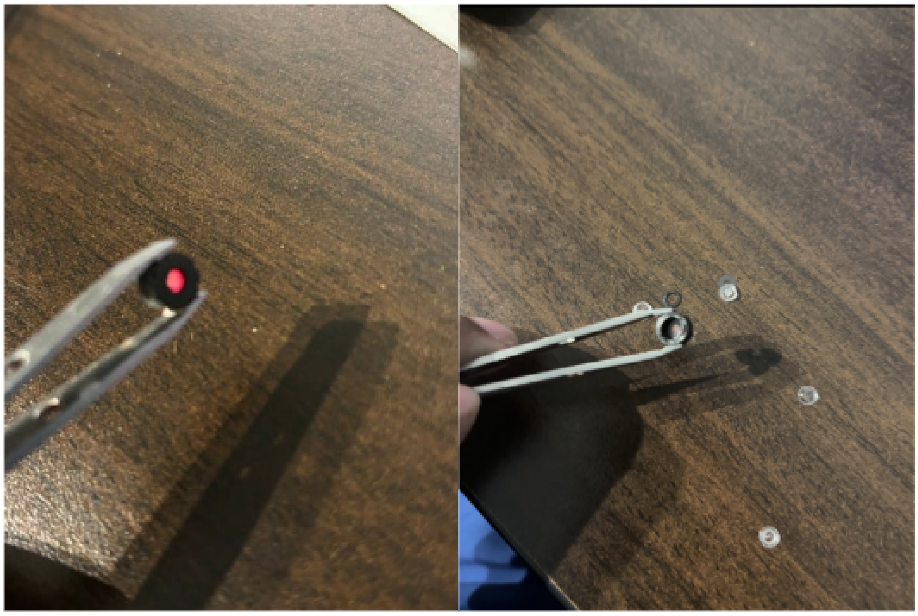
Appendix B

Irremovable IR filter on ESP32-CAM



Appendix C

Horizontal distance measurement for FOV specification fulfillment



Appendix D

Web Server Setup

```
// ESP32 Access Point Network Credentials
const char* ssid = "ESP32";          // SSID (WiFi network name)
const char* password = "12345678";   // Password

// Static IP Address details
IPAddress local_ip(192,168,1,1);     // User input into browser
IPAddress gateway(192,168,1,1);
IPAddress subnet(255,255,255,0);

// Start web server
AsyncWebServer server(80);


void setup() {
  // Initialise serial communication
  Serial.begin(115200);

  // Set up WiFi access point
  WiFi.softAP(ssid, password);
  WiFi.softAPConfig(local_ip, gateway, subnet);
  delay(100);

  // Launch SPIFFS
  if(!SPIFFS.begin(true)){
    Serial.println("SPIFFS Setup Error");
    return;
  }

  // Define HTTP routes and request handlers
  server.on("/", HTTP_GET, [](AsyncWebServerRequest *request){
    request->send(200, "text/html", getHomePageContent());
  });

  server.on("/library", HTTP_GET, [](AsyncWebServerRequest *request){
```

Appendix E

Usability Survey

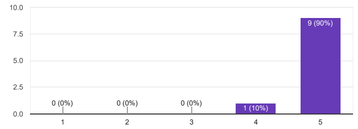
User Interface Usability Survey

10 responses

How easy was it to navigate through the user interface? Copy

Please rate your experience on a scale of 1 to 5, with 1 being that you really struggled and 5 being that you found it very simple to navigate.

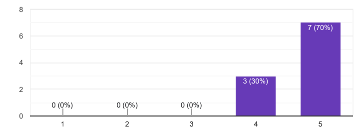
10 responses



Was the format of the displayed data and images clear and understandable? Copy

Please rate your experience on a scale of 1 to 5, with 1 being that the format was hard to understand and 5 being that you found it the format clear and easy to understand.

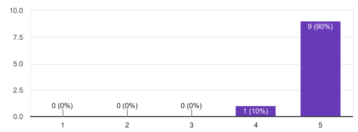
10 responses



Did you find the interface layout and design intuitive and user-friendly? Copy

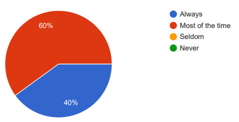
Please rate your experience on a scale of 1 to 5, with 1 being that you found the user interface to be not user-friendly at all and 5 being the opposite.

10 responses



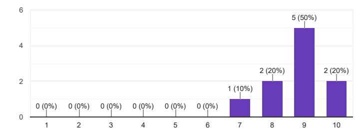
Did the interface respond promptly to your interactions and requests? Copy

10 responses



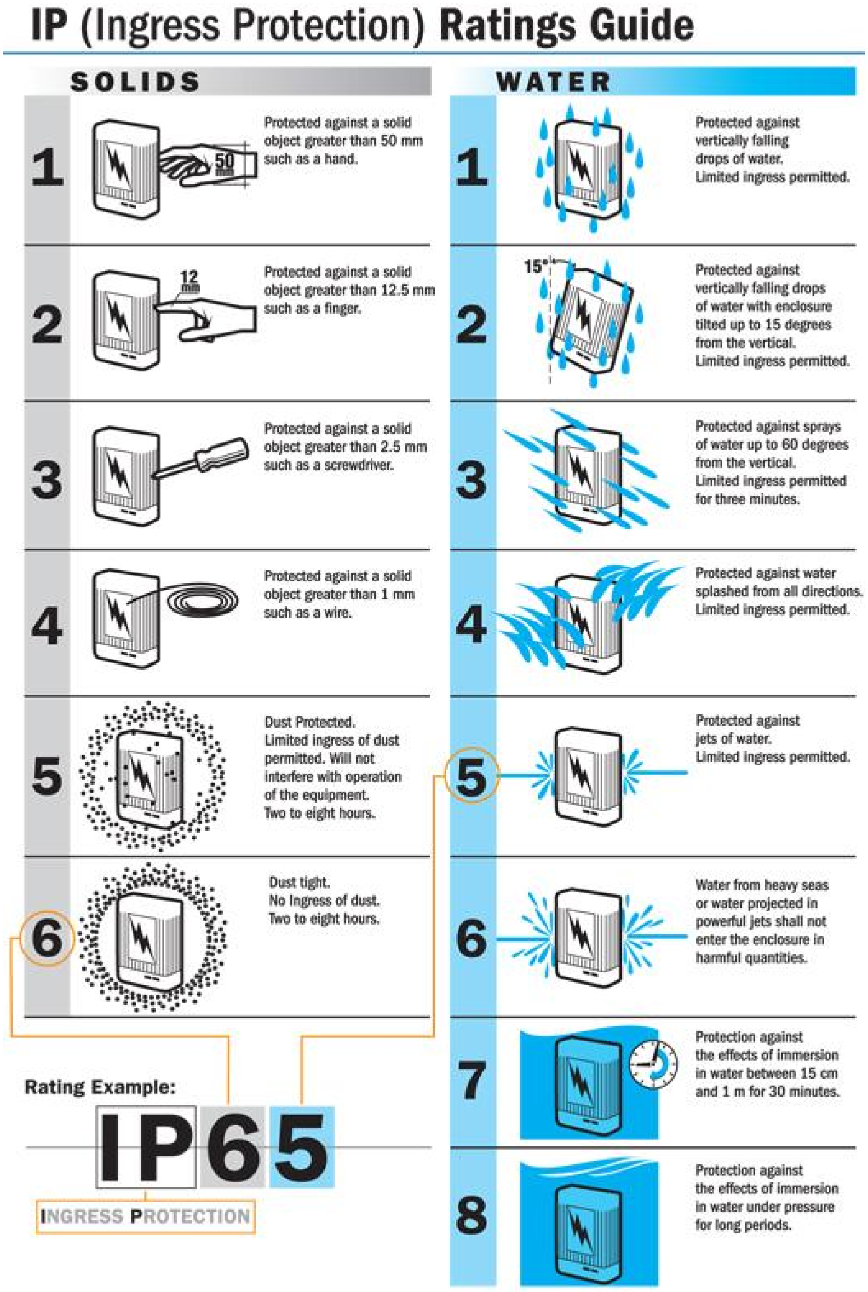
Please rate your overall experience of the usability of the web application on a scale of 1 to 10, with 1 being the worst usability and 10 being the best. Copy

10 responses



Appendix F

IP Rating scale



Appendix G

GA Requirement Analysis

Table G.1: KGHMIC001 GA Requirement Analysis

GA	Requirement	Justification
3	Engineering Design	Successfully designed and built power circuit for project. (See section 4.3)
7	Sustainability and Impact of Engineering Activity	Safe, effective, environmentally friendly methods followed. (See section 4.3 and 4.5)
8	Individual, Team and Multidisciplinary Working	Attendance at all D-school activities and team meetings. (See lit review, section 3)
10	Engineering Professionalism	Followed a comprehensive step-by-step process to complete the project. (See section 4)

Table G.2: NHLSIY008 GA Requirement Analysis

GA	Requirement	Description
3	Engineering Design	Successfully designed the contents of the sensor submodule for the project. This design included a schematic design, veroboard design aswell the added software coding of the project's sensors. (See section 5.4 and 5.5)
7	Sustainability and Impact of Engineering Activity	Safe, effective, environmentally friendly methods followed. (This project is aimed to be used for wildlife conservation, also see section 5.1)
8	Individual, Team and Multidisciplinary Working	Attended all D-school activities, engaged in MS teams group chat and attended face to face team meetings. (See problem analysis in section 2)
10	Engineering Professionalism	Attended all lectures presented by the course and arrived for scheduled consultations with the TA or the convener in a timely manner. Furthermore, all instructions and advise on how to complete the project was followed to the best of my abilities. (See section 5)

Table G.3: BHMQAI001 GA Requirement Analysis

GA	Requirement	Justification
3	Engineering Design	Designed and implemented a web server for the project. (Section 6.4 and 6.5)
7	Sustainability and Impact of Engineering Activity	Participated in D-School activities and group discussions to ensure the creation of a safe, environmentally friendly system. Designed a subsystem that does not affect the environment negatively. (Section 6)
8	Individual, Team and Multidisciplinary Working	Completed Sections 6 and 8, and contributed to Section 2 and the overall structuring of the report.
10	Engineering Professionalism	Attended all D-school activities, EEE4113F lectures and team meetings, and had timely submissions.

Table G.4: KRNNEN001 GA Requirement Analysis

GA	Requirement	Justification
3	Engineering Design	Designed,tested and constructed a physical enclosure for the system. (Sections 7.3 - 7.7)
7	Sustainability and Impact of Engineering Activity	Attended all D-School sessions which highlighted the conservation of wildlife, specifically birds. Subsystem hand no negative impact on environment and had no emissions or toxic byproducts (Section 7)
8	Individual, Team and Multidisciplinary Working	Participated in developing a problem statement and a solution to the problem statement as well as participating in section 2, and completed section 7.
10	Engineering Professionalism	Attended all team meetings, lectures, D-School activities and meetings with the lecturer. Kept to deadlines set both by the group and the course.

Appendix H

Bill of Materials and Git Repository

H.1 Bill of Materials

Part No.	Part Name	Quantity	Unit Cost (R)	Total Cost (R)
Power Sub-Module				
1	6V Solar Panel	2	149.95	299.9
2	TSAL61000 IR LEDs	4	10.53	42.12
3	18650 3V7 Battery + Holder	1	25	25
4	MCP1700 Voltage Regulator	1	9.57	9.57
5	TP4056 Charger Module	1	36.22	36.22
6	Veroboard (10x10cm)	1	16.04	16.04
7	100uF Electrolytic Capacitor	1	8.23	8.23
8	100nF Ceramic Capacitor	1	4.31	4.31
9	27k Ohm Resistor	1	0.35	0.35
10	100k Ohm Resistor	1	0.35	0.35
11	10k Ohm Resistor	1	1.16	1.16
12	10 Ohm Resistor	4	1.09	4.36
			Power Subtotal	447.61
Sensing Sub-Module				
13	ESP32-Wroom-32	1	149.95	149.95
14	ESP32-Cam	1	235	235
15	ArduCam SPI Mega	1	480	480
16	PIR Motion Sensor	1	28	28
17	SD Card Module	1	23	23
18	16 GB SD Card	1	56.01	56.01
19	Ambient Light Sensor	1	20	20
20	DS3231 RTC	1	60	60
			Sensing Subtotal	1051.96
User Interface Sub-Module				
			No Components - Subtotal	0
Hardware Module				
21	Plywood(0.6*150*80)	1	243	243
22	Glass pane (0.5*15*22)	1	135	135
			Hardware Subtotal	378
			Total Cost of Prototype	1877.57

H.2 GitRepo Link

See the Git repository at this link.