Final Report

Automated Predator Detection and Deterrence Using Radar, Cameras, and Water-Based Repellents

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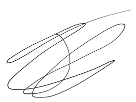

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Chapter 1

Introduction

As part of the 2025 EEE4113F design course, our class was approached by multiple stakeholders, each of whom presented unique conservation-related challenges that could benefit from technological solutions. After engaging with three different stakeholder groups, our team chose to work with Christina Hagen from BirdLife South Africa. Christina's project focuses on the protection of the endangered African penguin population at the De Hoop Nature Reserve, where predation by land-based animals poses a significant threat to penguin colonies.

We were tasked with developing a system capable of detecting and deterring predators before they could reach the penguins, all while minimizing disturbance to the natural environment , with no harm inflicted on the predators. Our proposed solution consists of three integrated subsystems: detection, deterrence, and real time surveillance.

The detection subsystem features a low-cost, radar-inspired design that utilizes an ultrasonic sensor mounted on a servo motor to perform continuous 180° environmental sweeps. The captured distance and angular data of potential threats are processed and wirelessly transmitted to a graphical radar interface, which displays the information in real time for easy monitoring. Additionally, the location data of detected threats is relayed to the deterrence subsystem, allowing targeted defensive mechanisms to be deployed based on the threat's position.

The deterrence subsystem functions as an active response mechanism to the detection subsystem within the predator protection framework. It employs a high-pressure water jet to safely and effectively repel predators from the designated penguin colony. Utilizing positional data provided by the detection module, the water deterrent system precisely aims and delivers a targeted jet stream, designed to cause discomfort and discourage intrusion without causing harm.

The user interface subsystem serves as the communication bridge between the detection and deterrence systems and the end user, enabling real-time interaction, data retrieval, and system monitoring. Designed with usability and accessibility in mind, this subsystem allows researchers to remotely monitor penguin predators, access and manage data collected by the detection unit, while also overseeing the operational status of the detection mechanism and viewing live surveillance footage. Built around developing a GUI, the subsystem leverages its onboard web server capabilities to host a minimalist, browser-based application compatible across various devices.

Chapter 2

Problem Analysis

Christina, a wildlife researcher studying endangered African penguins in remote coastal areas, requires a cost-effective system to prevent predation on the penguin population. The solution must operate reliably in areas with limited power and network connectivity, be weatherproof to withstand harsh coastal conditions, and provide real-time protection without causing significant harm to the target species or any non-target species. Additionally, the system should offer a remotely accessible, wireless GUI for real-time environmental monitoring to ensure effective and humane safeguarding of the penguins.

At D-school, we were introduced to creative thinking methods that emphasized collaboration and ideation. We engaged in activities that encouraged us to open our minds, challenge assumptions, and generate solutions through teamwork. Brainstorming sessions helped us explore a wide range of possible ideas, which we then narrowed down to the most promising concepts.

After several design thinking exercises, we shortlisted three main ideas for implementation: ultrasonic sensing for threat detection, high-pressure water jets for deterrence, and camera surveillance with a graphical user interface (GUI) for real-time monitoring. These choices were based on their practicality, cost-effectiveness, and ability to address the core problem efficiently.

Instead of choosing just one, we decided to integrate all three ideas into a unified system. Combining ultrasonic detection, water-based deterrence, and visual monitoring allowed us to create a robust and responsive threat detection and prevention system, enhancing both automation and user control.

Sensing Subsystem: An ultrasonic sensor mounted on a servo motor sweeps across an 180° range to detect approaching threats.

Deterrent Subsystem: On detection, location data is sent to high-pressure water jets, which then target and neutralize the threat.

User Interface Subsystem: Cameras record live footage and stream it via a GUI, while also capturing and saving screenshots to an SD card.

Chapter 3

Literature Review

3.1 Introduction

The conservation of endangered species, such as the African Penguin, requires the implementation of targeted strategies to minimize predation and protect vulnerable populations. Extensive research has led to the development of various technologies aimed at detecting and deterring predators, forming an integrated system that effectively mitigates threats to wildlife. Detection and deterrence are inherently interconnected, as an efficient conservation system must not only identify potential threats but also implement measures to prevent predation.

Given that these systems are often deployed in remote and environmentally harsh locations, it is essential to ensure their reliability and longevity. This necessitates the incorporation of key design considerations, including effective remote data capture, low power consumption for sustained operation, and weatherproofing to withstand extreme conditions.

This literature review examines the various methods used for predator detection and deterrence, evaluating their effectiveness in different environmental contexts. Furthermore, it explores the challenges of maintaining these systems in remote, weather-intensive, and energy-constrained environments, emphasizing the need for durable and efficient solutions in wildlife conservation efforts.

3.2 Animal Detection Devices

3.2.1 Infrared Devices

Haschberger et al. [1] presented a new application of Infrared (IR) sensors for the detection of game. The device detects wildlife such as mammals and birds by using the difference between IR radiation of the animals and the environment they're in. The system's purpose is to "save the animals' lives" [1] as well as for "wildlife management purposes" [1] which coincides with the theme of the problem statement of developing predation prevention devices to prevent the extinction of the African Penguin. Yusman et al. [2] similarly designed and built a wild animal pest-repellent gadget that contained a passive infrared (PIR) sensor. Likewise, it is used to detect the presence of wild animal objects through infrared rays. Furthermore, Pedersen and Pedersen [3] developed a novel activity-sensing system for measuring the movements of domestic animals. As with the previous model, it uses passive infrared detectors (PID). The system is "suitable for monitoring the total animal activity in a group of animals" [3], making it compatible when integrating into a penguin colony. On the contrary to the other two, its operation is based on the output analogue signal being proportional to the surface temperature and velocity of the animal in motion.

The three different systems vary quite a bit in terms of their hardware and software designs. The first model's instrument design is based on a minimum detectable temperature of 5K [1]. Due to a system requirement of needing it to function on agricultural machinery, an irregular and simple setup would suffice. Each sensor unit is equipped with optics that focus the radiation emitted by the measurement object to the detection element. The output of each sensor is fed to a comparator. If the signal level exceeds a preset threshold, an acoustic alarm is sounded with an LED display on the CPU indicating the signaling sensor [1]. Elsewhere, the second proposal consists of a computer unit, a micro-controller and the PIR sensor [2]. It focuses on measuring the sensitivity level of the detector. It follows that the final system simply used PIDs that are found in standard commercially available units [3]. This leads to problems in the detection process. Infrared radiation is restricted if poor contrast between the background and animal temperature is present. However, this can be combated by enhancing the difference with aid from an optical plastic lens.

As a result from testing, the sensor only worked consistently if operated in the morning or under a cloudy sky [1]. It must be stated that this limitation is independent of the sensor design, but due to the inherent principle of radiation detection. Moreover, the PIR sensor was able to detect up to a maximum distance of 5m for all animals monitored [2]. Lastly, the PID was accurate when sensing one moving body but "did not exhibit proportionality to multiple inputs" [3], which would be restrictive if a group of predators approached the African Penguins.

3.2.2 Thermal Devices

Christiansen et al. [4] sought out to contribute to the automated detection and classification of animals using thermal imaging. Furthermore, Popek et al. [5] studies compared the various methods of animal detection in thermal camera images. This included the classical approach and deep neural networks.

The methodology and subsequent results are based on top-view images taken manually in the attempt of motivating future works towards unmanned aerial vehicle-based detection and recognition [4]. This non-evasive implementation would be beneficial in not disrupting the natural ecosystems of the predators (e.g. leopards) and prey (e.g. penguins). The device works by detecting hot objects against a threshold that is dynamically adjusted to each visual frame and then using a novel thermal feature extraction algorithm for the classification of animals [4].

On the other hand, the classical approach has the following procedure: Pre-processing –> Segmentation –> Selection and Scaling –> HOG/SVM –> Visualisation [5]. The first step entails the removing of symbols left on the images by different cameras while the second groups pixels of similar brightness together.

Conversely, convolutional neural networks have gained traction in the context of object analysis in digital images [5]. Most of the solutions currently being used are based on fine-tuning, allowing for credible results. Yet it should be noted that most of the models are carried out on basic images. This means that scenarios with other characteristics on the images can potentially end up in failure. The researchers used two popular architectures: Faster R-CNN and YOLOv3 [5]. The former being a faster network whose operation is based on splitting graphics into stacked layers in search of specific features, while the latter maps regions of interest on the grid of the input.

The results from two of the three different undertakings proved to be successful. Using a k-nearest neighbour (kNN), animals are discerned from objects with a “balanced classification accuracy of 84.7 % in an altitude range of 3-10 m and an accuracy of 75.2 % for an altitude range of 10-20” [4]. From this, it can be determined that the thermal radiation sensed by the detector decreases as the distance to the animal increases. Thus, introduction of a tracking algorithm to incorporate temporal information increased the percentages for both ranges [4].

As for neural networks, it correctly coped with the problem of classification and finding objects in thermal images, but the classical model could not achieve this [5]. As the problem statement is only concerned with the detection of a predator and not the species specifically, the limitation of not being able to differentiate different animals of the same species is not critical. Although, detection of animals in a compact group may prove difficult as their silhouettes can potentially overlap [5]. Therefore, in the long run, modules to remove such problems need to be implemented.

3.2.3 Solar and SARD

Mishra and Yadav [6] presented a solution that utilises the Internet of Things (IOT) and machine learning in the form of a Smart Animal Repelling Device (SARD). The purpose of it is it safeguard crops from wildlife as it posing a threat to human welfare. This is achieved through the development of virtual fences that use artificial intelligence (AI) and ultrasonic emission. Correspondingly, Reddy et al. [7] aimed to protect the crops on farms from damage caused by animals as well as scare them away without any harm being caused. Both proposals rely on an animal detection system and come about this realisation in similar manners.

The SARD integrates a PIR sensor, solar panel and Low Range (LoRa) technology for real-time, energy-efficient animal detection [6]. Using a Single Shot Multibox Detector (SSMD) with the R-CNN architecture, the accuracy and speed of animal identification is improved. Simultaneously integrating this with AI to enable continues monitoring and decision-making processing, an accuracy with a rate of 95% in association and detection was achieved.

In comparison, the circuit designed to be placed on solar based fences also made use of a PIR sensor. By contrast, it is interfaced with a Raspberry Pi [7]. The input signal sent by the sensor turns a camera on and captures the image of the animal, with an alert also being sent to the farmer. The internal operation of the PIR involves the converting of the radiation picked up by the sensor into an output voltage, triggering the detection. Regarding the solar fence, this concept is sustainable for energy consumption as it makes use of an indefinitely renewable energy source. As the system operates with a GSM sim modem, one can utilise it remotely.

One limitation that both designs face is when an animal roams through the area where there are two sensors with cameras in proximity with one another. The potential for it be wrongfully identified as two distinct creatures exists [7]. The algorithm used for re-identification is limited when animals transition between different cameras. The Interaction over Union (IoU) can be used to combat this [6].

Ultimately, the seamless integration of animal detection and repelling mechanisms allows for quick and precise reactions to identified predators [6]. A vital component in keeping danger away from the penguins, this aspect is an encouraging positive. This is further reinforced by the testing results, which demonstrated the effectiveness of the SARD. Notable numerical metrics included an "accuracy of 91.88 %, precision of 87.37 %, recall of 91.01% and an F1 score of 89.83 %" [6], illustrating successful implementation. Though, there are obstacles that need to be overcome. The adaptation of the current functionalities to accommodate a wide range of terrains and weather needs to be explored. This is important as the penguins are both terrestrial and aquatic animals.

3.3 Devices utilized for animal deterring purposes

Various techniques have been explored for the development of devices designed to deter unwanted animals from specific locations. Gilsdorf et al. [8] highlights the significance of understanding an animal's auditory and visual perception in designing effective deterrent mechanisms. As noted by the authors, "Visual and acoustic sensitivity varies according to taxon, species, sex, and age of the animal" [8, p30]. This variability necessitates a tailored approach when selecting or designing deterrent systems.

The visual perception of animals is largely determined by the composition of their retinas, which contain rod and cone cells. Rod cells are highly sensitive to light, whereas cone cells facilitate colour vision [9]. Nocturnal species tend to have rod-dominated retinas, allowing for enhanced vision in low-light conditions [10], while diurnal species rely more on cone cells for colour discrimination and daylight vision [9]. Consequently, visual deterrents must consider these physiological differences to ensure effectiveness across various species.

Similarly, the efficacy of acoustic deterrents depends on an animal's sensitivity to sound frequency and pressure. Frequency, measured in Hertz (Hz), and sound pressure, measured in decibels at sound pressure level (dB SPL), play a crucial role in determining an animal's responsiveness to auditory stimuli [8]. Understanding these parameters allows for the optimization of sound-based deterrents to elicit the desired behavioural responses.

Deterrent devices can be categorized based on their primary function, such as visual, auditory, or physical mechanisms. The following sections provide a detailed analysis of the effectiveness of each category based on existing research.

3.3.1 Visual devices

A variety of visual techniques have been implemented in animal deterrence applications. Gilsdorf et al. [8] investigated the use of laser-based deterrents to disperse bird and mammal species. Two laser types were tested: the Desman© laser, a helium-neon laser, and the Dissuader® laser, a red diode laser [8]. However, the efficacy of these methods remains limited. VerCauteren et al. assessed the effectiveness of these lasers in deterring deer from agricultural fields at night, reporting that only 5.6% of encounters resulted in the animals fleeing [11].

Alternative visual deterrents have demonstrated greater potential. Stone et [12] al. examined the use of high-powered halogen spotlights, operated by night guards to scan sheep enclosures and surrounding areas, thereby deterring potential predators. However, in remote locations, such systems would require automation to maintain effectiveness. Building upon this concept, Foxlights have been introduced as an automated deterrent solution. This device utilizes LED lights that flash irregularly to create the illusion of human presence, thereby increasing a predator's perceived risk and reducing the likelihood of predation [12].

These findings highlight the importance of selecting visual deterrents based on species-specific behavioral responses and environmental constraints. However, considerations need to be made as to whether such devices provide long term solutions against animal habituation.

3.3.2 Auditory devices

Auditory deterrent devices have been widely explored as a means of mitigating depredation, employing various techniques to disrupt animal activity in targeted areas. Ultrasonic devices, which operate by emitting high-frequency sounds beyond the human auditory range, have been investigated as a potential solution for pest control [8]. Examples of such devices include the Yard Guard and Usonic Sentry, both of which are motion-activated and designed to emit ultrasonic frequencies for durations ranging from 7 to 18 seconds [8]. However, their effectiveness remains limited, as Belant et al. (1998) [13] found that the Yard Guard failed to deter deer, while the Usonic Sentry demonstrated only short-term efficacy, with deterrence lasting no longer than one week.

An alternative auditory deterrent approach involves bioacoustics, which utilizes distress calls to repel animals from designated areas [8]. The effectiveness of this method appears constrained, as Koehler et al. [14] acknowledge that the application of bioacoustics to reduce mammalian damage has been limited. Further supporting this observation, Wade [15] highlights that distress calls exhibit only short-term and inconsistent effects on coyote behaviour, thereby limiting their practicality in long-term wildlife management strategies.

More disruptive auditory deterrent techniques involve the use of high-intensity noise devices, which aim to startle and disorient animals. Klaxons, or loud air horns, have been deployed alongside blank-firing handguns to deter predators. In this approach, a .22-caliber starter pistol was discharged into the air in the presence of predators, reinforcing the deterrent effect through sudden and unpredictable noise [12]. Expanding on this concept, Belant et al. (1996) [16] examined the efficacy of propane cannons and deer-activated gas exploders, which periodically emit loud explosive sounds. Their study found that deer took approximately six weeks to habituate to these devices, suggesting that such methods may provide more sustained deterrence [16].

Overall, the evidence indicates that high-intensity auditory deterrents, particularly those incorporating explosive sounds, are more effective in mitigating animal habituation. While ultrasonic and bioacoustic methods may offer limited short-term benefits, the unpredictability and disruptive nature of loud noise-based deterrents make them a more viable option for long-term wildlife control.

3.3.3 Physical devices

Physical deterrent methods are widely employed in various wildlife management and depredation control applications. Musiani et al. [17] describe fladry as a barrier system consisting of red or orange plastic flags (50×10 cm) attached at 50cm intervals along a nylon rope (0.2cm in diameter), which is suspended 50cm above the ground and supported by metal rebar posts spaced at 30m intervals. Lance et al. [18] further developed this approach by incorporating an electrified rope, known as 'turbo-fladry,' to enhance its deterrent effect. Stone et al. [12] note that this method is primarily effective against wolves.

On a larger scale, Reddy et al. [7] propose the use of solar-powered electric fencing as a more advanced deterrent measure. In this system, photovoltaic cells capture solar energy and convert it into electrical energy, which is stored in batteries to supply power to an astable multivibrator incorporating a 555-delay timer. A free-running oscillator generates a square wave signal, ensuring that the fence delivers intermittent pulses rather than continuous shocks. This signal is amplified via a push-pull amplifier before being stepped up to high voltage using a transformer, enabling the fence to deliver an electric shock upon contact [7].

Among various deterrent techniques, physical barriers—particularly electric fencing—have demonstrated long-term effectiveness in restricting animal movement. The use of deterrents that cause temporary discomfort has been found to reduce the likelihood of habituation, thereby increasing their efficacy in wildlife control.

3.3.4 The importance of integration of multiple animal deterring devices

The most effective strategy for preventing habituation is the implementation of integrated deterrent approaches [8]. One such example is the Electronic Guard, a device specifically designed to mitigate coyote predation on sheep and livestock. This system comprises a timer, a flashing strobe light, and a warbling siren, all enclosed within a polyvinyl chloride casing. It is equipped with a built-in photocell that automatically activates the system at sunset and deactivates it at sunrise. During operation, the timer randomly triggers the device, emitting flashes and sounds for approximately 7–10 seconds, with activation occurring at intervals of 6 to 7 minutes throughout the night [19] [20].

Linhardt et al. [20] found this integrated system to be effective in safeguarding sheep from coyote predation during the summer. The author further suggests that habituation can be delayed if deterrent devices are deployed in sufficient numbers, repositioned periodically, and programmed to introduce variations in light and sound patterns [20].

The potential of integrated deterrent methods to minimize habituation and provide long-term wildlife management solutions is significant. However, Gilsdorf et al. [8] highlight a lack of research comparing the effectiveness of individual deterrent techniques with integrated approaches. This gap underscores an opportunity for further investigation into comprehensive wildlife deterrence strategies and their comparative efficacy.

3.4 Remote Data Capture , Power Consumption and Weatherproofing

3.4.1 Utilizing the Raspberry Pi Micro-controller for Remote Data Capture

Several studies have demonstrated the viability of Raspberry Pi for remote monitoring applications, particularly due to its compact design, affordability, and ability to support various peripherals. Reddy et al.[7] integrated Raspberry Pi with passive infrared (PIR) sensors and cameras for agricultural monitoring, leveraging its 'credit card-sized single board' [[7], pg. 188] and its capacity to support a wide range of sensors and modules. This flexibility in deployment made it suitable for various applications. However, as the monitoring system expanded, processing demands grew, necessitating a RAM upgrade from 256 MB to 512 MB [1]. This highlights the scalability limitations of Raspberry Pi for large-scale or data-intensive applications. Similarly,Hereward et al.[?] used Raspberry Pi for ecological monitoring, taking advantage of its low cost and programmability. However, they encountered challenges related to data storage, as the limited capacity of the SD card hindered long-term data collection [21].

Success rates in remote data collection, particularly in challenging environments, vary based on factors such as network connectivity. Hereward[21] reported a 70% success rate across 138 deployments when using Raspberry Pi in remote, isolated locations [21]. One of the primary challenges identified was the lack of reliable network connectivity, which led to data being stored on SD cards. While this solution initially worked, it had limitations, as SD cards often failed to accommodate the large amounts of data generated over extended periods. Mouy et al.[22] encountered similar constraints when deploying underwater fish cameras, relying on a 200 GB SD card to record up to 212 hours of video data over 8 to 14 days. Additionally, Greene et al. [23] achieved successful 30-day deployments by implementing a system that captured 30-second video clips or took photos twice daily when triggered by sensors.

USB storage was explored as an alternative to SD cards, but the results were mixed. Mouy [22] reported that USB storage usage was energy-intensive and prone to disruptions caused by vibrations in marine environments [22]. Conversely, Kallmyer et al. [24] successfully used a 32 GB USB drive in their remote monitoring setup without reliability issues. This variation in performance suggests that the effectiveness of USB storage may depend on specific deployment conditions, such as environmental factors and the nature of the data being collected.

3.4.2 Exploring Solar and Battery Solutions for Remote Monitoring

Powering Raspberry Pi systems in remote environments presents significant challenges, particularly in areas without reliable access to conventional power sources. While solar power is an attractive solution due to its renewable nature, several studies have highlighted its limitations. Notably, there are 'few commercially available solar modules that exceed 22% efficiency' [[7], pg. 184], and static solar panels struggle with seasonal and daily variations in sunlight. To address these challenges, researchers have explored alternative approaches to optimize energy collection. Linelson and Saputri [25] proposed using AI-driven proportional-integral-derivative (PID) control to dynamically adjust the orientation of solar panels, ensuring they track the sun's position throughout the day. This optimization increased energy output by up to 46% [25], significantly outperforming static setups that were limited by fixed panel angles and environmental fluctuations.

Although AI-based tracking systems can improve energy efficiency [25], there are also simpler and more cost-effective alternatives. Youngblood [26] proposed using phone-charging power banks to sustain Raspberry Pi systems in remote locations, achieving up to four days of continuous operation before requiring replacement. This method is relatively inexpensive and avoids the complexity of AI-driven solutions. However, it requires frequent human intervention for replacing power banks, which may not be feasible for long-term remote applications. However, for high-power demands, such as powering electric fences, AI-driven solar tracking may remain the most viable option due to its ability to sustain high-energy requirements over long periods.

A hybrid approach that combines battery packs with solar power has also been explored. For instance, Mouy experimented with a seven-stack configuration of four EBL D-Cell rechargeable batteries in series, totalling 70,000 mAh, which extended operational longevity over a 14-day test period [22]. This hybrid setup strikes a balance between the affordability and convenience of power banks [26] and the efficiency of AI-enhanced solar tracking [25]. While it lacks the adaptability and efficiency of AI-driven systems, it reduces reliance on frequent battery replacements and provides sufficient power for larger systems, such as solar-powered fences [7].

3.4.3 Environmental Durability and Weatherproofing Strategies

One of the critical challenges in deploying remote monitoring systems is ensuring they remain durable and functional in harsh environmental conditions. Effective weatherproofing of Raspberry Pi units requires a careful balance between protecting the equipment from the elements and maintaining accurate data collection. Britzke et al. [27] and Bolton et al. [28] explored the use of PVC enclosures, which are affordable, widely available, and resistant to physical damage. In the study done by Britzke, a microphone for bat call detection was enclosed in PVC piping, providing effective protection from mechanical harm. However, this protection came at a cost—detected call sequences were reduced by 30% due to acoustic interference from the PVC material [27]. This example illustrates the trade-off between durability and data integrity, where materials offering high protection might negatively impact data collection performance.

Similarly, Bolton used PVC for underground artificial nest chambers, benefiting from its UV protection and long lifespan of up to 10 years [28]. While PVC offers several advantages, it may not always be the most suitable option for all environmental conditions. For more cost-conscious solutions, Hereward experimented with silicone-sealed Tupperware enclosures for remote monitoring devices[21]. Initially, this method provided good short-term protection against moisture and dust. However, within a month, humidity exposure caused the enclosures to fail, stating '80% of the cameras had ceased to function due to humidity' [[21], pg. 7]. This highlights the limitations of low-cost weatherproofing solutions, which may offer protection in the short term but lack the durability required for long-term deployments in harsh environments.

Glass-reinforced plastic (GRP), also known as fiberglass, is gaining attention as a durable alternative to traditional materials like PVC and Tupperware. Ensure Port Limited [[29]] highlights GRP's exceptional resistance to moisture and corrosion, which enhances its longevity in demanding environments. However, despite these benefits, GRP's brittleness makes it vulnerable to cracking under mechanical stress, raising concerns about its reliability in high-impact applications.

In contrast, polyester electrical boxes, as noted by Safybox [30], present a more robust solution, particularly for outdoor applications. Unlike GRP [10], polyester is not only corrosion-resistant but also exhibits superior heat resistance and UV stability, ensuring longevity even in extreme weather conditions. Safybox further emphasizes the significance of heat resistance [30], a crucial factor when housing electronic components.

This aligns with findings from Prinz, A. C. B. et al. [31], who discuss microcontroller performance in controlled enclosures, demonstrating successful operation across a wide temperature range (1.1°C to 37.8°C). The ability to withstand such conditions reinforces polyester's suitability over GRP.

3.5 Conclusion

This literature review has explored the advancements and solutions developed over the years in the fields of animal detection, deterrence, and system robustness, particularly in resource-constrained and remote environments.

The integration of modern technologies has significantly improved the accuracy and efficiency of predator detection, with infrared sensing combined with machine learning and artificial intelligence proving to be the most precise approach. The success of the Solar SARD system exemplifies the potential of leveraging contemporary technologies to enhance wildlife protection.

In terms of deterrence mechanisms, research has shown that integrated systems combining physical, auditory, and visual techniques yield the highest success rates in preventing predator habituation. The Electronic Guard serves as a prime example of an effective multi-faceted deterrent, utilizing flashing lights and loud sounds to disrupt predator behavior and improve long-term efficacy.

However, the effectiveness of these systems is ultimately dependent on their ability to function in remote, power-limited, and environmentally harsh conditions. Ensuring sustained operation requires the implementation of energy-efficient micro controller based solutions, such as the Raspberry Pi, along with reliable power sources, including battery and solar energy systems. Additionally, robust weatherproofing materials and enclosures are essential to protect these systems from extreme environmental conditions.

By integrating these elements—a comprehensive and effective approach to wildlife conservation can be achieved , ensuring long-term sustainability and effectiveness in protecting endangered species such as the African Penguin.

Chapter 4

Detection Subsystem(MCHJOH015)

Prepared by MCHJOH015

4.1 Introduction

This project presents the development of a low-cost radar-based detection system designed to monitor animal movement in real-time and support automated deterrent mechanisms by providing the necessary data required to locate the threat. The system employs an ultrasonic sensor mounted on a servo motor to perform continuous 180 ° environmental sweeps. The distance and angular data of the threat are gathered, formatted into structured messages, and transmitted wirelessly via UDP(User Datagram Protocol) using an ESP32 microcontroller, allowing off-site monitoring. A custom-made graphical radar interface visualizes these data in real time, enabling researchers and conservation staff to monitor activity remotely without disturbing the habitat.

4.2 Requirements and Specifications

4.2.1 User Requirements

UR #	User Requirement
UR-01	The system must detect potential predator threats while ensuring no harm to non-target species such as penguins, terns, and cormorants.
UR-02	Detection readings must be accurate and repeatable to ensure reliable operation and effective threat identification.
UR-03	Sensor data must be transmitted wirelessly in real-time to enable off-site monitoring and timely response.
UR-04	The system must have low power consumption and operate efficiently from a 12V, 1A power source to suit remote, resource-limited environments.
UR-05	The entire sensing unit must be waterproof and weather-resistant to function reliably in harsh outdoor conditions.
UR-06	The system must be easy to install and relocate, with minimal environmental impact and no permanent alterations to the site.

Table 4.1: User Requirements

4.2.2 Requirement Analysis

Through an in-depth analysis of the user requirements, a set of corresponding design specifications was developed. Each specification is directly linked to an acceptance test, which serves to validate both its feasibility and effectiveness. These acceptance tests ultimately act as measurable criteria to assess the success of the final system. The specifications, derived from the user requirements, are outlined below.

SP #	Design Specification	Acceptance Test Procedure (ATP)
SP-01	Perform a full sweep from 0° to 180° to detect objects.	Verify servo performs full sweep and sensor records distance at each angle without triggering on small, non-target objects.
SP-02	Provide readings with ±3cm, effective up to 1 meter.	Compare sensor outputs against known distances; repeat tests to confirm consistency and reliability.
SP-03	Transmit distance and angle data wirelessly in structured format: "Angle:30, Distance:50".	Verify data packets are received correctly, parsed accurately, and displayed in real-time on the radar interface.
SP-04	A buck converter steps down 12V to required 5V/3.3V power rails with >80% efficiency.	Measure voltage stability and thermal output under typical and peak load to confirm low power operation.
SP-05	Electronics are enclosed in a weather-sealed housing that resists dust, water, and mechanical wear.	Conduct moisture, vibration, and durability tests to validate environmental durability.
SP-06	The sensor system is housed in a lightweight, portable enclosure.	Evaluate ease of installation and removal, confirm no lasting environmental damage or footprint.

Table 4.2: Design Specifications and Corresponding Acceptance Test Procedures

4.3 Hardware Design Decisions

4.3.1 Sensor Design Decisions

Sensor	Voltage	Current	Cost	Range	Accuracy	Type
HC-SR04	5V	15 mA	R75	2–400 cm	±3 mm	Ultrasonic
JSN-SR04T	5V	20–30 mA	R160	20–600 cm	±10 mm	Ultrasonic
GP2Y0A21 (IR)	4.5–5.5V	30–40 mA	R90	20–600 cm	10–20 mm	Infrared

Table 4.3: Sensor Specifications Comparison

The HC-SR04 ultrasonic sensor was selected for its optimal balance of cost, accuracy, and power efficiency. With a precision of ±3 mm and low current draw (15 mA), it met the system's need for high-resolution sub-1m detection without exceeding the shared 1A power budget. Its affordability (R75) ,ease of integration with Arduino IDE and the ESP32 Microcontroller made it the ideal choice. Alternatives like the JSN-SR04T and GP2Y0A21 were rejected due to higher cost, lower accuracy, greater power consumption, and functional limitations, such as poor night-time performance and non-linear output when using and infrared sensor(GP2Y0A21).

4.3.2 Technical Overview of the Sensor

The ultrasonic distance detection system uses the HC-SR04 sensor, which operates on the time-of-flight principle. It emits a high-frequency 40 kHz pulse via the `TRIG` pin and measures the time it takes for the echo to return using the `ECHO` pin. To trigger a reading, `TRIG` is set LOW for 2 μs, then HIGH for 10 μs. The sensor emits an 8-cycle ultrasonic burst and sets `ECHO` HIGH until the reflected signal is received, after which it goes LOW.

The ESP32 uses the `pulseIn()` function to measure how long `ECHO` stays HIGH, then calculates distance with:

$$\text{distance (cm)} = \frac{\text{duration}(\mu s) \times 0.03432}{2}$$

The division by 2 accounts for the round trip (to and from) of the sound wave.

Logic Level Protection: Since the HC-SR04 outputs 5V and the ESP32 uses 3.3V logic, a voltage divider (2 kΩ and 1 kΩ resistors) steps down the `ECHO` signal to approximately 3.3V, preventing damage to the ESP32's GPIO. The output voltage is calculated as:

$$V_{\text{out}} = 5\,\text{V} \times \frac{1\,k\Omega}{1\,k\Omega + 2\,k\Omega} \approx 3.3\,\text{V}$$

The voltage divider circuit was tested in simulation to determine whether it affected the accuracy of the sensor readings and was proven to be effective as both set-ups attain the same result as shown below.

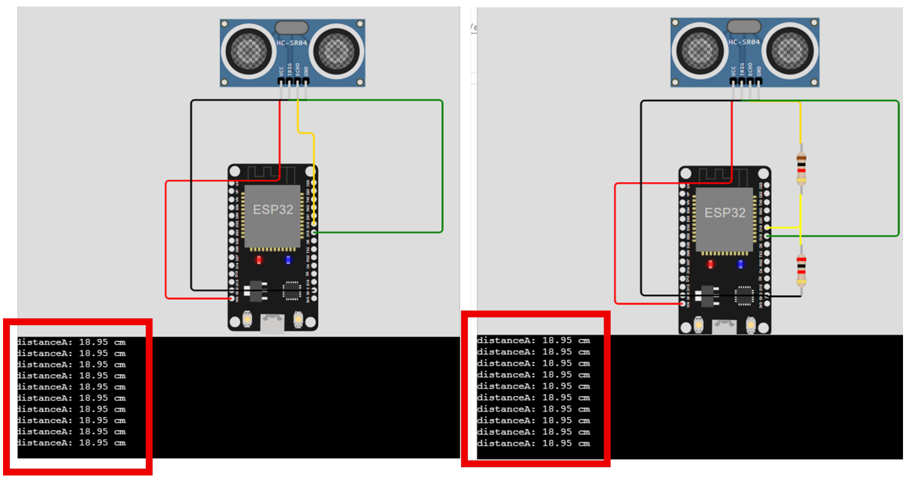


Figure 4.1: Comparison of sensor simulation results without (left) and with (right) voltage divider circuit

4.3.3 Servo Design Decisions

Servo	Voltage	Torque	Dead Band	Gears	Feedback
SG90	4.8–6V	1.8 kg · cm @ 4.8V	10 µs	Nylon/Plastic	Within DC motor
MG90S	4.8–6V	2.2 kg · cm @ 4.8V	20 µs	Metal	None
XL330-M288-T	4–8.4V	3.5 kg · cm @ 6V	<5 µs	Metal	Yes

Table 4.4: Servo Specifications Comparison

The SG90 micro servo was selected for its practical balance of torque, responsiveness, and cost. Delivering 1.8 kg · cm torque, it provided sufficient force to rotate the ultrasonic sensor and its housing smoothly. Its 10 µs dead band allowed for responsive radar sweeps, which were critical for accurate readings. Despite having plastic gears, wear was considered acceptable for a limited-use prototype. Importantly, its low cost (R60) enabled the deployment of three servos in the overall system without exceeding budget constraints. Alternatives like the MG90S and XL330 were not selected due to higher cost, with only marginal or unnecessary performance benefits for this application.

4.3.4 Technical Overview of the Servo

The ESP32 controls the SG90 servo using PWM (Pulse Width Modulation), which means it turns a digital pin on and off very quickly in a precise pattern. The servo expects a signal every 20 milliseconds (50 times per second), and the length of the ON time in each signal tells it which angle to move to. A 1.0 ms pulse means 0° (far left), 1.5 ms means 90° (center), and 2.0 ms means 180° (far right), with values in between moving the servo to in-between angles. This relationship is linear and depicted in Figure 4.2 below. Inside the servo, there's a small component which reads this signal, checks the current angle using a built-in potentiometer, and adjusts a small DC motor until the angle matches the command.

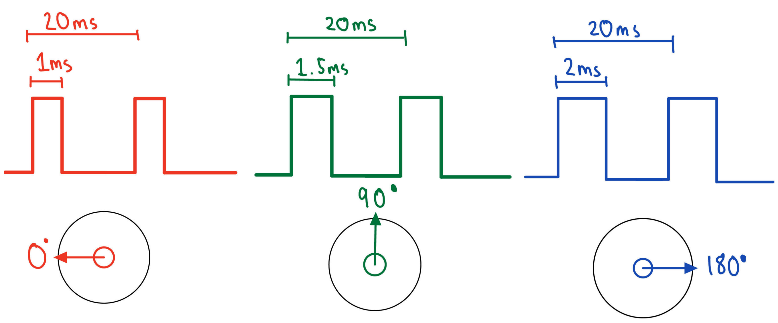


Figure 4.2: Graphical illustration showing how PWM signal width maps to servo angles.

The function "pulseln()" ,extracted from the ESP32 servo library is used to convert the PWM signal into its respective angle.

4.3.5 Housing Design Decisions

The housing of the subsystem was designed to balance durability , weatherproofing and stability. It consists of a recycled glass jar for the base, a custom 3D printed PLA mount for the sensor , and a laser-cut Perspex outer shell for protection from elements and to provide support structure for other subsystems.

Material	Evaluation & Decision Summary
Laser Cut Perspex	• Perspex was chosen for its stability, whilst offering aesthetic appeal • Its moderate strength, low cost, and ease of fabrication using a laser cutter made it ideal for rapid prototyping. • Laser cutting proved significantly faster, more reliable, and less complex than 3D printing for box creation. • Silicone sealant was applied along the joints to ensure waterproofing. • A design error in connection slot settings left small gaps between parts, potentially allowing water ingress,this will be corrected in future iterations.
Glass Jar	• A recycled glass jar was used as the base due to its natural waterproofing properties, ideal for containing electronics. • Originally designed to hold liquids, it has natural waterproofed capabilities. • Its heavy weight provided crucial stability, especially with a top-heavy 3D-printed section mounted on a servo. • Only minimal wiring holes were required; these will be sealed with tubing and silicone in future versions for waterproofing . • The recycled nature of the jar supported both cost-saving and sustainability goals.
3D Printed PLA	• Used for internal sensor mounting, PLA allowed custom geometry for the ultrasonic sensor. • Enabled effective routing of wires toward the back, supporting controlled motion during servo rotation with wires getting tangled. • Located inside a sealed enclosure, limiting exposure to water despite not being waterproof itself. • A protective 'hat' was integrated to shield the sensor from potential droplets from the deterrence subsystem. • Lightweight and affordable, well-suited for geometrically sensitive, non-load-bearing applications.

Table 4.5: Material Evaluation and Design Decisions

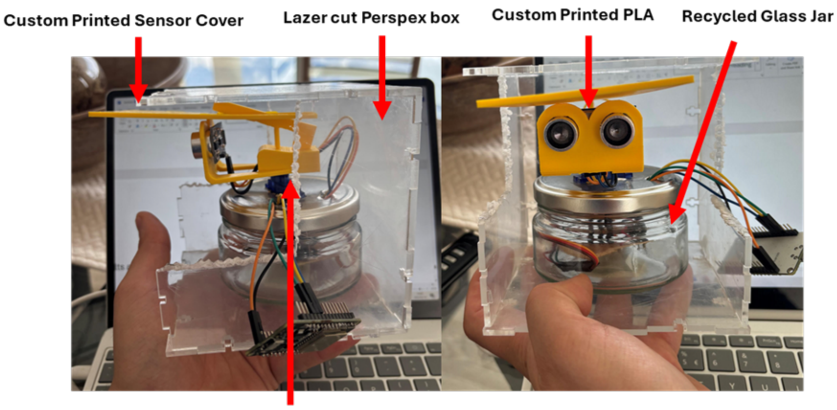


Figure 4.3: Descriptive image of 3D-Printed Sensor Mount , Base and Enclosure

4.3.6 Microcontroller Design Decisions

Microcontroller	Clock Speed	Logic Level	Wi-Fi	Max GPIO Current	Cost
ESP32	240 MHz (dual-core)	3.3V	Yes	12 mA	R120
Raspberry Pi Pico W	133 MHz	3.3V	Yes	12 mA	R140
Arduino Uno	16 MHz	5V	No	40 mA	R160

Table 4.6: Microcontroller Specifications Comparison

The ESP32 was chosen primarily due to its built-in Wi-Fi capabilities, which were essential for meeting the project's requirement of remote access .Additionally, the ESP32 offered significantly lower power consumption, making it ideal for power-limited or battery-operated deployments. Its dual-core 240 MHz processor provided ample performance for handling sensor inputs, servo actuation, and real-time communication to the radar , outperforming the single-core Pico W and the much slower Arduino Uno. While the 3.3V logic on the input ports required minor voltage adaptation for compatibility with 5V sensors, this was easily addressed using a voltage divider. Overall, the ESP32 provided the best combination of connectivity, efficiency, and processing capability at the lowest cost, making it the most suitable choice for the system.

4.4 Software Design Decision

The GitHub repository for this project can be found at:
https://github.com/mchjoh015/EEE4113F_Sensing_subsytem_MCHJOH015

The software integrates the system's hardware into one cohesive unit. It controls the servo motor to sweep between 0° and 180°, while the ultrasonic sensor detects objects and measures their distance and angle. This data is sent via Wi-Fi using the UDP protocol—a fast, lightweight method of sending data—to a laptop identified by its IP address. The laptop then displays the data through a simple radar-style GUI, visually showing object positions in real time.

Figure 4.4 below illustrates the software logic of a radar-like object detection system using an ESP32, a servo motor, and an ultrasonic sensor. The process begins with the inclusion of key libraries (WiFi.h, WiFiUDP.h, and ESP32Servo.h) and the configuration of Wi-Fi credentials, UDP communication parameters, and pin definitions. During the setup() phase, the servo and sensor pins are initialized, a connection to the Wi-Fi network is established, and serial communication begins. In the loop() function, the servo motor continuously sweeps from 0° to 180° and back. At each angle, the servo is updated using myServo.write(angle), followed by a short delay to allow for physical movement. The ultrasonic sensor is triggered to measure the distance to any object in its path by sending a pulse and capturing the return echo; the time is converted to distance using the formula distance = duration × 0.0343 / 2. Any distance exceeding 100 cm is capped. A data packet in the format 'angle,distance' is created and transmitted via UDP to a designated IP address and port, where it is used by a remote device to render a graphical radar interface.

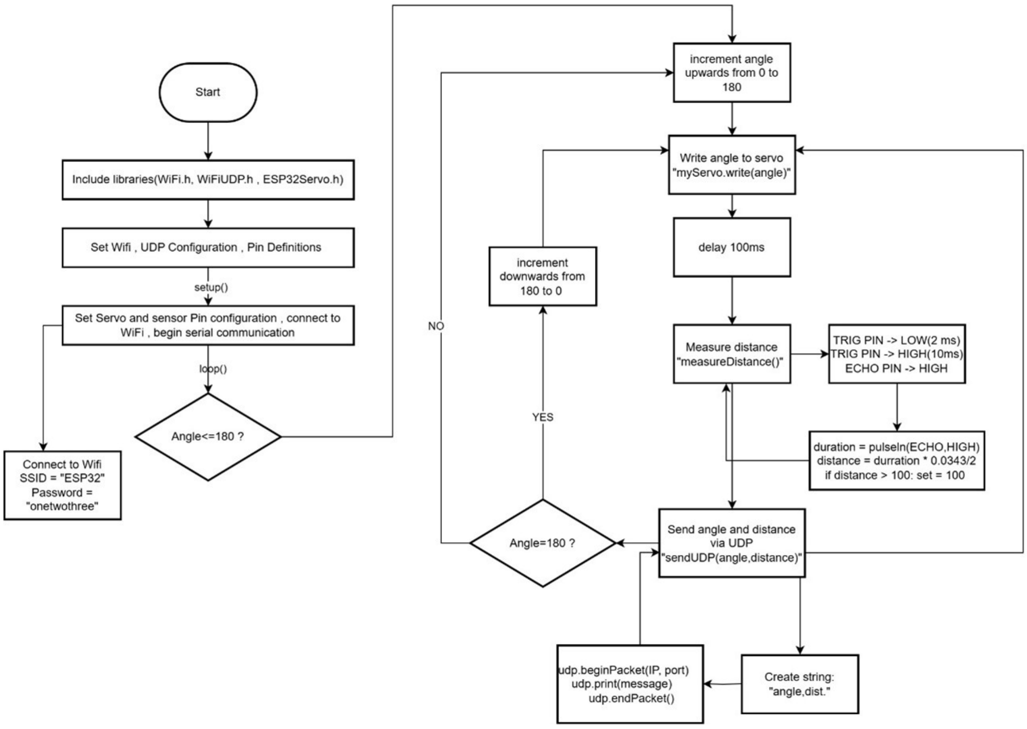


Figure 4.4: Software logic of a radar-like object detection system

4.4.1 Communication Protocol Design Decision

Protocol	Reliability	Latency	Overhead	Complexity
UDP	None (no ACK)	Very Low (5–30 ms)	Minimal	Low
TCP	High (ACK + retransmit)	High (100–300 ms)	High	Medium
MQTT	High (QoS, retained messages)	Medium (50–150 ms)	Moderate	High (requires broker)

Table 4.7: Communication Protocol Comparison

UDP was specifically chosen for this project because, despite its lack of reliability due to the absence of acknowledgments or retransmissions, it offered a significant advantage in speed. In real-time applications like radar-based object detection, timely data delivery is more critical than guaranteed delivery. UDP's ability to send data without waiting for confirmation means that information about object distance and angle can be transmitted almost instantly, allowing for smooth and responsive radar sweeps. While protocols like TCP and MQTT are more reliable due to their use of acknowledgments and delivery guarantees, these features introduce delays and increase overhead, which can result in lag and outdated visualizations on the graphical user interface. In this case, slight data loss was considered acceptable, as the system continually updates with new readings.

4.4.2 Technical Overview of UDP Protocol

Figure 4.5 clearly shows why UDP was the preferred choice over TCP for real-time data transmission, such as in a radar system. With UDP (top half), the sender (ESP32) simply sends a request, and the receiver (Laptop) immediately replies with multiple responses, without waiting for acknowledgments. This makes the communication very fast and efficient, which is ideal for scenarios like radar sweeps, where data must be updated rapidly for smooth visual feedback.

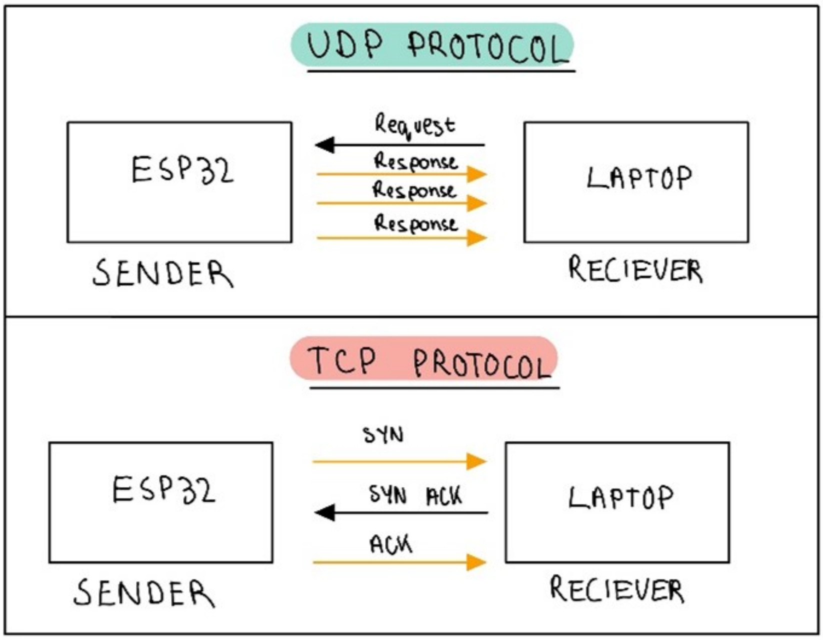


Figure 4.5: UDP vs TCP

In contrast, the TCP protocol (bottom half) involves a three-step handshake (SYN → SYN-ACK → ACK) before any data is transferred. This handshake introduces noticeable delay and overhead, as the sender waits for confirmation before proceeding. While this ensures reliable transmission, it is too slow for real-time applications, where missing a few packets is better than lagging behind.

4.4.3 Technical Overview of Radar Software

During the first 20 seconds, the servo will sweep while the sensors scan the area to detect all existing objects. This process ensures that already present objects are not mistaken for threats. An array is used during calibration to store the positions of these detected objects. During detection, the system checks this array and ignores any object that has already been stored, preventing it from being detected again. After this initial scan, the radar begins detecting new objects, marking them with a red 'X'. Existing objects are indicated by green glowing dots, as shown in the Figure 4.6. Additionally, the angle and distance of the detected object are displayed in the bottom left corner.

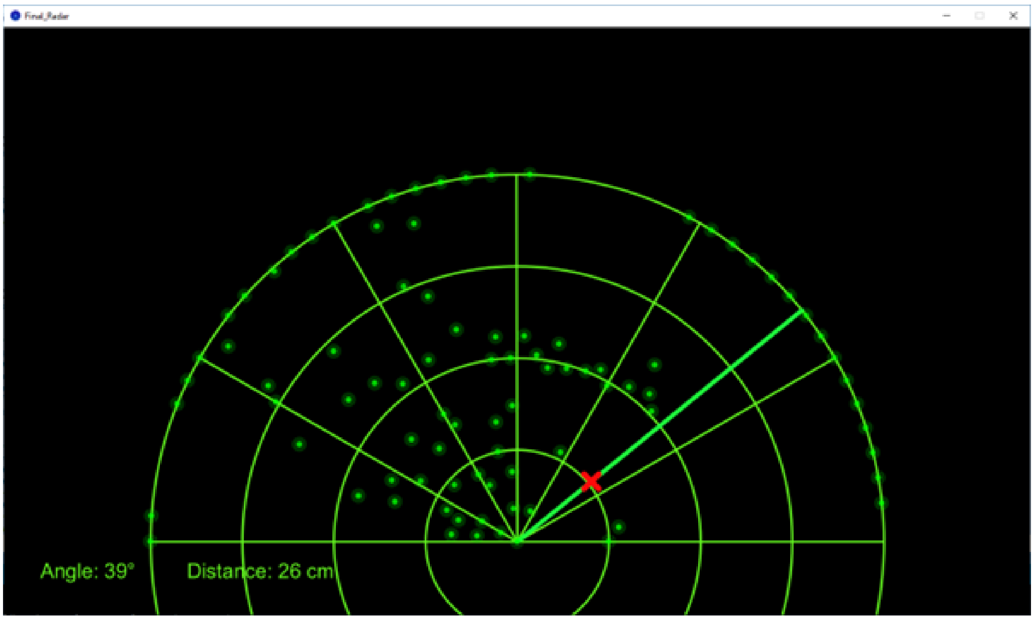


Figure 4.6: Graphic illustration of Radar after Calibration

Figure 4.7 below illustrates the logic implemented in the radar software, along with a detailed description of some of the more insightful functions provided on the right side of the figure.

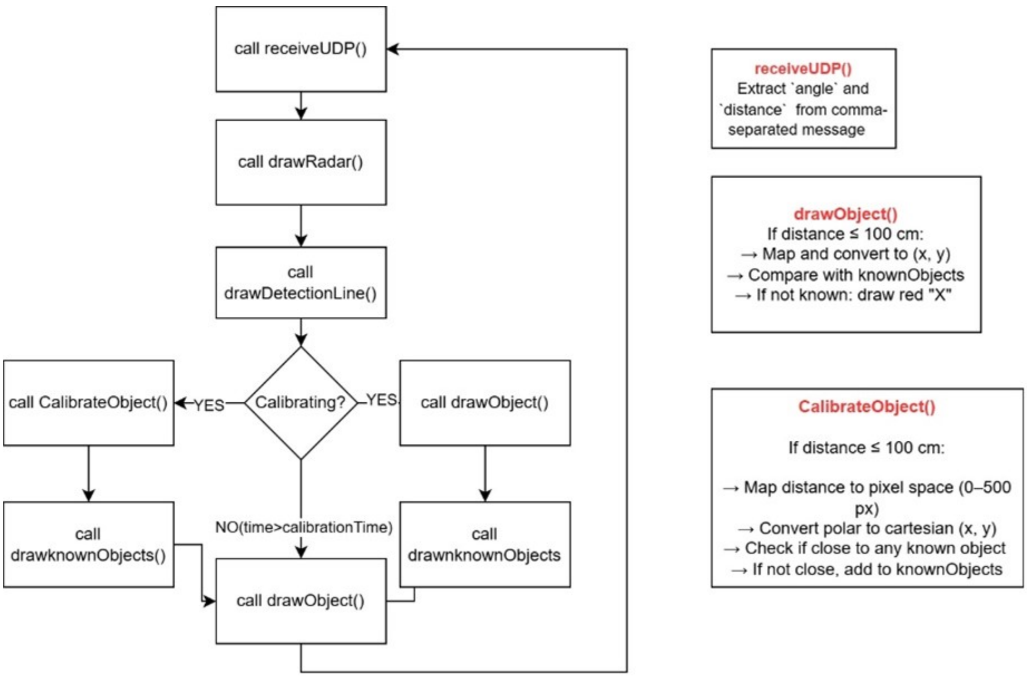


Figure 4.7: Block Diagram Showcasing Radar Software Operation

4.5 Acceptance Tests and Results

ID	Test Description	Result
ATP-01	Servo performs 0°–180° sweep; sensor detects objects without false triggers.	Pass
ATP-02	Sensor provides ±10mm accuracy, 5mm resolution up to 1m; repeatable results.	Pass
ATP-03	Sends data in "Angle:30, Distance:50" format; received and displayed correctly.	Pass
ATP-04	Buck converter outputs 5V/3.3V from 12V input with >80% efficiency under load.	Pass
ATP-05	Electronics sealed against dust/water; withstands moisture, vibration, and wear.	Pass
ATP-06	Portable enclosure; easy install/removal; no environmental damage.	Pass

Table 4.8: Compact Acceptance Test Summary

4.5.1 HC-SR04 Sensor Testing and Results(ATP-02 ATP-03)

Actual (cm)	Angle (°)	R1	R2	R3	Avg (cm)	Err (±cm)
30	0	29	30	30	29.67	-0.33
30	90	30	31	30	30.33	+0.33
30	180	30	30	31	30.33	+0.33
60	0	59	60	61	60.00	0.00
60	90	61	60	62	61.00	+1.00
60	180	60	61	58	59.67	-0.33
90	0	89	92	91	90.67	+0.67
90	90	93	90	92	91.67	+1.67
90	180	89	91	94	91.33	+1.33
Statistical Accuracy Summary						
Range (cm)	**Mean Err (cm)**		**Std Dev (cm)**		**Max Dev (cm)**	
30	0.33		0.27		1.0	
60	0.44		1.25		2.0	
90	1.22		1.73		4.0	

Table 4.9: HC-SR04 Sensor Readings and Statistical Summary

4.5.2 HC-SR04 Sensor and Radar Effectiveness Testing Results

The HC-SR04 sensor demonstrated high accuracy at close range, with minimal error and low deviation from actual distances. However, its accuracy declines with distance due to weaker echo signals, lower signal-to-noise ratio, greater timing uncertainty, and environmental influences like temperature and humidity. These factors reduce the reliability of distance measurements at longer ranges. To enhance performance, especially over greater distances, improvements could include signal processing techniques to detect weaker echoes, experimenting with sensor positioning or using multiple sensors, and incorporating temperature and humidity sensors to adjust for environmental changes.

4.5.3 Buck Converter Testing and Results(ATP-04)

The system was powered by a 12 V battery, requiring regulated 5 V and 3.3 V outputs for the ESP32 and peripherals. Initially, 3.3 V was supplied directly to the ESP32, but only 2.3 V was observed at the output pins (see Figure below).2.3V was not sufficient to power the system. Further investigation revealed that the ESP32's VIN pin requires a 5 V input, which the onboard regulator converts to 3.3 V.

To prevent over-voltage damage, the buck converter outputs were verified using a digital voltmeter, confirming stable 5.0 V and 3.3 V levels before connection(see Figure 4.8). This ensured safe and reliable power to all components.

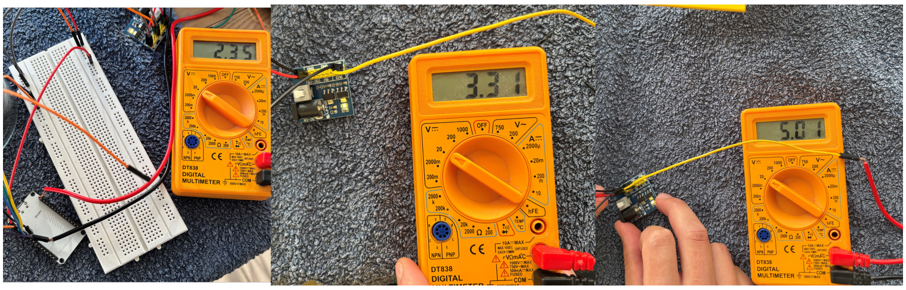


Figure 4.8: Voltmeter readings for ESP32 Output Pin and buck converters 3.3 and 5V output pins

Efficiency Calculation for 5V Rail

$$\eta_{5V} = \frac{\text{Output Power}}{\text{Input Power}} \times 100 = \frac{1.60\,\text{W}}{1.92\,\text{W}} \times 100 = 83.3\%$$

Efficiency testing showed the buck converter maintained over 80% efficiency. Input/output voltages and currents were measured, and power calculations confirmed minimal losses. This high efficiency is essential for reducing heat , which causes power loses and maximizing battery life in the system.

Since the buck converter often overheated, there was a concern it could fail and allow 12V to reach components rated for 5V and 3.3V. Therefore, further research should include the use of heat sinks or other thermal management solutions to reduce the risk of overheating. In addition, the design should incorporate robust protection mechanisms such as MOSFET-based circuits, diodes, and fuses to guard against over-voltage, over-current, and reverse polarity events.

4.5.4 Servo Sweep and Static object detection Testing and Results(ATP-01)

During the 20-second calibration phase, the servo continuously performed sweeps from 0° to 180° and back while the sensor scanned the environment. Stationary objects (I used rocks and lamps simulating trees) placed within the field of view were recorded as background. In all subsequent scans, these objects were consistently ignored, confirming the system's ability to distinguish between pre-existing and newly introduced objects. Further research could explore improving calibration by using Machine learning to help the system better recognize complex background patterns.

Test Item	Result Summary
Weight Measurement	Subsystem weighed at **846 grams**, confirming it is lightweight and easy to handle.
Environmental Impact Test	After repeated installation on various surfaces, no permanent marks, scratches, or residue were observed. No lasting environmental damage.
Transport Test	Subsystem carried by hand and in a backpack over a 500 m walk. No physical damage or loose components detected.

Table 4.10: ATP-06 Acceptance Test Summary

4.5.5 ATP-06: Portable Enclosure Acceptance Testing(ATP-06)

Further research could test the subsystem's durability under harsher transport conditions, such as vibration or impact during vehicle travel. Long-term wear tests could assess environmental impact after extended use.

4.6 Sensitivity Analysis

Parameter	Values	Effect
UDP frequency	5, 10 (default), 20 Hz	5 Hz: Laggy updates; 10 Hz: Smooth, real-time; 20 Hz: Faster, some packet loss.
Servo delay	50, 100 (default), 200 ms	50 ms: Jitter/skips; 100 ms: Stable; 200 ms: Stable, slower scan.
Distance threshold	70, 100 (default), 150 cm	70 cm: Missed far objects; 100 cm: Balanced; 150 cm: Noisy detections.
Angle step	1°, 2° (default), 5°	1°: High detail, slower; 2°: Good balance; 5°: Fast, low resolution.
Calibration time	10, 20 (default), 30 s	10s: Missed some; 20s: Reliable; 30s: Same as 20s.

Table 4.11: Effect of Key Parameters on System Performance

4.7 Conclusion

The prototype system was successful in all six acceptance tests. The HC-SR04 ultrasonic sensor demonstrated high accuracy in short and medium ranges, with consistent object detection and reliable filtering of static background elements during the successful 180 degree servo sweep calibration. The enclosure was proved to be weatherproof lightweight, easy to transport, and did not cause environmental damage during repeated use. Power regulation using the buck converter showed high efficiency (83%),whilst outputting the required voltages.Overall, the system was successful, functioning as intended.

Chapter 5

Deterrence Subsystem (CRSKAT005)

This subsystem is designed to develop a high-pressure water deterrent that integrates seamlessly with the existing detection mechanism to repel predators from the penguin colony. A small-scale prototype has been developed to demonstrate the core functionality of the proposed system, serving as a foundational step toward a practical, full-scale implementation for field deployment. This chapter outlines the key design decisions and strategies aimed at delivering a functional, cost-effective, and reliable solution to the depredation challenge, and discusses the translation of the prototype into a fully operational field-ready system.

5.1 Requirement Analysis

5.1.1 User Requirements

Requirement ID	User Requirement
UR01	The system must be able to deter a predator.
UR02	The system must be able to respond to a desired position as to where the predator has been detected.
UR03	The system must not cause long-term harm to the predator.
UR04	The system must be water and weather proof.
UR05	The system must consume low amounts of power and save power when not in use.

Table 5.1: Summary of User Requirements

5.1.2 Specifications

From Table 5.1, the following specifications for the subsystem have been derived:

Specification ID	Description	Derived from
SP01	The prototype's water spray shall reach a horizontal distance of at least 1m, with each activation lasting 5 seconds.	UR01

Specification ID	Description	Derived from
SP02	The system shall calculate and adjust its firing orientation to align with a target identified at an angular offset of 0°–180° horizontally and a horizontal distance of up to 1m from the sensor, with a response time of less than 500 milliseconds.	UR02
SP03	No spray event shall exceed 5 seconds per activation cycle.	UR03
SP04	The system enclosure shall provide protection against environmental dust and be resistant to rainfall and splashing water from any direction. It shall remain fully operational in ambient temperatures ranging from –10°C to 50°C.	UR04
SP05	The system prototype shall operate continuously on a 12V DC, 1A power supply.	UR05

Table 5.2: System Specifications Derived from User Requirements

As outlined in Table 5.2, Specifications SP01 and SP05 pertain specifically to the prototype model. In a deployable version of the system, these specifications would need to be revised to accommodate a larger-scale deterrent capable of actively repelling predators. This would likely involve increased power requirements and enhanced performance capabilities. For instance, the water spray mechanism would need to project a stream reaching at least 5 meters to ensure effective deterrence in real-world conditions. Specifications SP02-04 are all necessary in both a prototype and deployable model.

5.1.3 Acceptance Tests

To evaluate the success of the defined specifications, a series of acceptance test procedures have been developed. These procedures serve as structured guidelines for verifying system performance and guiding further refinement and improvement of the prototype.

Acceptance Test ID	Testing	Description
ATP01	SP01	**Distance Test:** Measures the maximum horizontal range the water jet can achieve under normal operating conditions.
ATP02	SP01, SP03	**Timing Test:** Records the duration of each spray cycle to ensure it aligns with the specified activation time.
ATP03	SP02	**Accuracy Test:** Verifies that the water jet directs its water line at a specified target.
ATP04	SP02	**Response Test:** Verifies that the subsystem accurately aligns to the detected target location within 500 milliseconds of receiving the sensor input.

Acceptance Test ID	Testing	Description
ATP05	SP04	**Environmental Test:** Assesses the system's durability by exposing it to dust and moisture to verify weather resistance and operational integrity.
ATP06	SP05	**Power Test:** Verifies system functionality and stability while operating within the specified power supply limits.
ATP07	SP01–SP05	**Reliability Test:** Operates the system continuously through repeated activation cycles over an extended period to evaluate long-term performance.

Table 5.3: Acceptance Tests Derived from System Specifications

5.2 Design Decisions and Theory

5.2.1 Structural Design

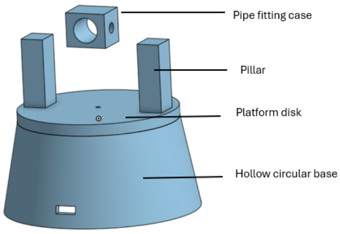
Before selecting and comparing components for the module, it was essential to finalize the structural design of the water jet system in alignment with the previously defined specifications.
The initial design consideration focused on meeting the requirements outlined in SP02—specifically, how the deterrence mechanism should respond to a detected target based on its angular offset and distance from the sensor. To address this, several hardware configurations were evaluated for the response mechanism:

Design Option	Assessment
Linear Actuator	Considered as an alternative to rotational mechanisms. Challenges include translating rotational sensor data into linear motion and the need for longer actuators to cover a wide detection range, which would increase response time and reduce efficiency.
Horizontal Rotational Mechanism Only	Effective in covering a wide horizontal range. However, targeting objects at varying distances is difficult without complex adjustments to water pressure and jet velocity, impacting precision.
Pan and Tilt Mechanism	Determined to be the most viable solution. Provides horizontal panning (up to 180°) and vertical tilting for precise targeting across wide areas and varying distances. Offers flexibility and efficiency for deterrence.

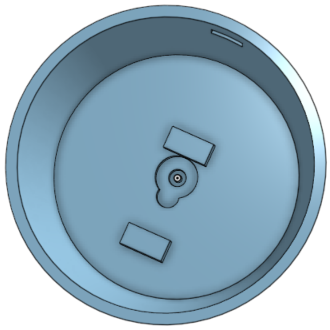
Table 5.4: Comparison of Mechanical Targeting Mechanisms

With the pan and tilt mechanism selected as the preferred hardware configuration, further design considerations were evaluated to ensure compliance with specifications such as SP04. In particular, the housing of the rotational components was assessed to ensure protection against harsh environmental conditions. The following design variations were developed using online CAD software and considered for implementation:

Pan and Tilt Design 1:



(a) Initial design idea for pan and tilt mechanism



(b) Inside design of hollow base for servo fitting

Figure 5.1: Pan and Tilt Prototype Design Considerations

The mechanism uses a pan servo housed in a circular base for horizontal rotation, with two tilt servos mounted vertically on the rotating plate for angular control of the water jet. This configuration offers compact integration, protects the pan servo from the environment, and provides stable support for the spray mechanism. It enables precise, responsive actuation—key for effective predator deterrence.

Advantages	**Disadvantages**
Pan servo is neatly housed within the base, protecting it from environmental exposure.	Use of three servos increases power consumption and current demands.
Pipe fitting offers secure and suitable support for deterrent spray delivery.	Dual-tilt servos introduce mechanical complexity and control overhead.
	Increased system complexity reduces design simplicity and reliability.
	Tilt servos remain exposed to environmental elements, requiring additional protective housing.

Table 5.5: Advantages and Disadvantages of Pan and Tilt Mechanism Design 1

Pan and Tilt Design 2:

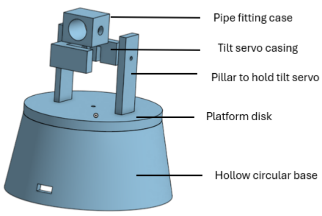


Figure 5.2: Improved Pan and Tilt Mechanism

The revised mechanism builds on the strengths of the initial design while addressing its limitations, retaining key advantageous components. In this improved configuration, the pan servo is securely housed within the platform, with reduced mechanical load due to the removal of an additional servo on the rotating platform disk. Using only two servos improves energy efficiency and avoids the coordination challenges posed by the dual-tilt setup in the original design. Furthermore, the tilt servo is better protected, minimizing exposure to environmental elements and enhancing durability. The selected pipe fitting remains a reliable solution, effectively supporting the system's intended deterrence functionality.

After finalizing the structural design, components for the deterrence subsystem—servos, microcontrollers, pumps, and spray jets—were researched and selected based on performance, compatibility, and suitability for the application.

5.2.2 Servo Motors

The servo motor decisions can be seen in Table 5.6, with comparisons between critical characteristics.

Servo Model	**Dimensions (mm)**	**Gear Type**	**Torque (kg-cm)**	**Response Time (s/60°)**	**Cost (ZAR)**
SG90 Mini	23 × 12.2 × 29	Plastic	1.80 @ 4.8V	0.12 @ 4.8V	32.00
MG996R Metal	40.7 × 19.7 × 42.9	Metal	9.00 @ 4.8V	0.19 @ 4.8V	105.00
DFRobot Clutch	23 × 12 × 27.3	Plastic	0.32 @ 4.8V	0.10 @ 4.8V	91.20

Table 5.6: Comparison of Servo Motors for Deterrence Subsystem

The SG90 Mini Servo was selected due to its low cost, compact size, and fast response time, making it ideal for the pan-and-tilt mechanism of the deterrence subsystem. While its torque is lower and plastic gears less durable than metal alternatives, its overall balance of performance, integration ease, and affordability made it the most suitable choice.
Following the selection of this servo motor, the dimensions of the of the final pan and tilt hardware design were adjusted to fit the dimensions of the SG90 Servo.

5.2.3 Microcontrollers

Two microcontrollers were evaluated for their suitability in integrating the hardware and software components of the subsystem, as well as enabling seamless connectivity between the detection and deterrence subsystems.

Microcontroller	**Choice**	**Wireless Connectivity**	**GPIO and Size**
ESP32-WROOM	Yes	Built-in Wi-Fi and Bluetooth for seamless integration with user interfacing and sensing subsystems.	More GPIO pins and compact size allow integration of sensing and deterrent subsystems on a single board.

Microcontroller	Choice	Wireless Connectivity	GPIO and Size
Arduino Uno	No	Requires external modules for wireless functionality, increasing cost and complexity.	Fewer GPIO pins and larger size make integration more difficult and require larger housing.

Table 5.7: Comparison of Considered Microcontrollers

While both microcontrollers were capable of meeting the software requirements for the deterrence system hardware, the selection was ultimately influenced by key features that were critical to the performance and integration of the detection subsystem.
Both the selected servo and microcontroller required 5V DC input. To regulate the 12V input supply, an HKD DC-DC converter was implemented.

5.2.4 Water Pumps

As per Specification SP01, the pump needed to provide adequate flow rate and pressure to effectively reach a 1m target. While high-performance pumps were preferred for reliability, power consumption also had to align with prototype constraints. A 5V, 1 channel relay module was selected to control the switching of the pump. Table 5.8 compares two candidate pumps based on performance and power efficiency.

Pump Model	Flow Rate	Power Consumption	Operating Voltage	Cost
ZKSJ DC40-1240	450 L/hr (7.5 L/min)	2.5W–28.8W	5V–12V DC	R250
SEAFLO Low Voltage Submersible Pump	960 L/hr (16 L/min)	48W Maximum	12V DC	R500

Table 5.8: Comparison of Candidate Pumps for the Deterrence Subsystem

The ZKSJ pump was selected for the prototype due to its versatility in both power consumption and operating voltage range, making it a suitable and reliable candidate for early-stage development and testing. While this pump meets the requirements for the prototype, a more powerful pump with a higher flow rate and increased pressure output would be necessary for a fully deployed, in-field system. Such a pump would be better equipped to achieve extended spray range and deliver a more effective deterrent response against predators.

5.2.5 Water Jet Attachment

To effectively deter predators from a penguin colony, the water stream must be concentrated into a thin, high-pressure jet capable of causing discomfort. Although the ZKSJ pump uses 10mm diameter piping, the outlet must be significantly constricted to generate the desired stream. At the pump's rated flow rate of 450L/h, the resulting water velocity is calculated as follows:

$$Q = A \cdot v \tag{5.1}$$

where:

- Q: volumetric flow rate (m^3/s)
- A: cross-sectional area of the pipe (m^2)
- v: velocity of the fluid (m/s)

Given a flow rate of $450\,\mathrm{L/h} = 1.25 \times 10^{-4}\,\mathrm{m^3/s}$ and a tube diameter of $10\,\mathrm{mm} = 0.01\,\mathrm{m}$, we compute:

$$A = \pi \left(\frac{d}{2}\right)^2 = \pi(0.005)^2 = 7.85 \times 10^{-5}\,\mathrm{m^2} \tag{5.2}$$

$$v = \frac{Q}{A} = \frac{1.25 \times 10^{-4}}{7.85 \times 10^{-5}} \approx 1.59\,\mathrm{m/s}$$

According to the continuity equation for fluid flow, $A_1 v_1 = A_2 v_2$, the water velocity can be significantly increased by reducing the cross-sectional area at the outlet. To achieve this, an irrigation nozzle was attached to the piping, secured in place by the pipe fitting case, as shown in Figure 5.3.

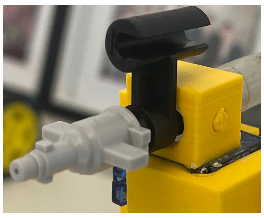


Figure 5.3: Irrigation attachment held in pipe fitting case

The irrigation nozzle had a 6mm diameter at the point of connection, while the pump required 10mm piping. To accommodate this difference, a reduction tube was used to adapt the larger pipe to the smaller attachment. The exit point of the attachment is approximately 1mm in diameter, resulting in the following calculated water exit velocity:

$$\begin{aligned} v_1 &= 1.59\,\mathrm{m\,s^{-1}}, \quad A_1 = 7.854 \times 10^{-5}\,\mathrm{m^2}, \quad d_{exit} = 1\,\mathrm{mm} = 0.001\,\mathrm{m} \\ A_{exit} &= \frac{\pi d_{exit}^2}{4} = 7.854 \times 10^{-7}\,\mathrm{m^2} \\ v_{exit} &= \frac{A_1 v_1}{A_{exit}} = \frac{7.854 \times 10^{-5} \times 1.59}{7.854 \times 10^{-7}} = \frac{1.248 \times 10^{-4}}{7.854 \times 10^{-7}} \approx 158.9\,\mathrm{m\,s^{-1}} \end{aligned}$$

This theoretical calculation suggests that the exit velocity of the water could be up to 100 times greater than the velocity within the main pump line, based solely on cross-sectional area differences. However, such a velocity increase is not physically realizable in practice due to real-world factors such as pressure limitations, frictional losses, and the inefficiencies inherent in nozzle flow.

Despite these constraints, the analysis confirms a significant increase in water velocity at the nozzle exit, enhancing jet reach and overall effectiveness. This improvement directly contributes to better performance of the deterrence subsystem. A water pressure of 50–70 PSI—corresponding to a velocity of approximately 26–32m/s—is sufficient to cause discomfort to an animal. Even accounting for expected system limitations, this level of jet strength remains achievable.

5.2.6 Final Hardware Design

Figure 5.4: Final Hardware Design

The final design incorporates an additional perspex overhead cover to provide protection while allowing unrestricted movement of the pipe at the rear of the mechanism. In the prototype, wiring was enclosed in clear plastic tubing, and the microcontroller along with other electronics was housed in a plastic container. For a future field-deployable model, all electronics would be enclosed in an IP65-rated housing, and electrical wiring would be routed through PVC conduit to ensure full environmental protection and compliance with weatherproofing standards.

5.2.7 Software Design Decisions

https://github.com/justincross10/EEE4113F_CRSKAT005_Deterrence_Subsystem/tree/main
In order to meet SP01 and SP02, the subsystem required some software to be written to control response and spray time lengths. Figure 5.5 illustrates a flow diagram of the algorithm layout for the software.

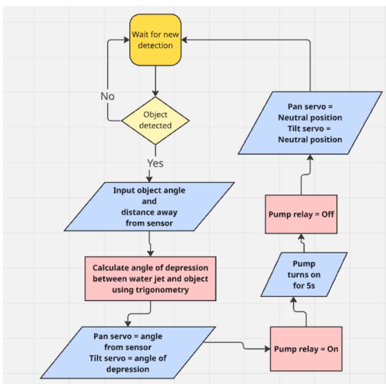


Figure 5.5: Flow Chart representing Software Algorithm

The flowchart includes a key step: calculating the angle of depression from the water jet to the target. Since the nozzle is mounted 20cm above the sensor base, this vertical offset must be accounted for. The angle of depression informs the tilt adjustment needed by the servo to accurately aim the jet. This was calculated using basic trigonometry, as shown in Figure 5.6.

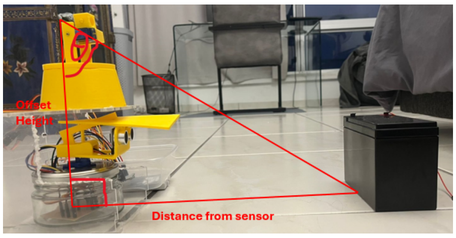


Figure 5.6: Image illustrating Angle of Depression

$$\theta_{\text{depression}} = \arctan\left(\frac{d_{\text{object}}}{h_{\text{offset}}}\right) \tag{5.3}$$

5.3 Testing and Results

The subsystem was tested according to the ATPs defined in the Requirements Analysis. Table 5.9 summarizes the test outcomes, with detailed procedures and improvement recommendations provided thereafter.

ATP ID	Test Type	Pass/Fail
ATP01	Distance Test	Pass
ATP02	Timing Test	Pass
ATP03	Accuracy Test	Pass
ATP04	Response Test	Pass
ATP05	Environmental Test	Fail
ATP06	Power Test	Pass
ATP07	Reliability Test	Pass

Table 5.9: Summary of Acceptance Test Results

5.3.1 Testing Procedures and Results Discussion

ATP01

The test was conducted by attaching the irrigation nozzle and powering the pump with a 12 V DC supply. The water jet distance was measured with a tape measure and found to be approximately 3 meters. This result significantly exceeded the prototype requirement of 1 meter, demonstrating the water jet system's reliable performance.

ATP02 and ATP04

To verify system performance, two key response tests were carried out. The first involved timing the water jet spray duration to ensure it matched the configured 5 second setting. The system consistently met this requirement, satisfying Specifications SP01 and SP03. The second test assessed the pan and tilt mechanism, measuring the time taken to reorient toward a target. With an average response time of approximately 150ms—well below the 500ms limit—the system demonstrated fast and reliable actuation.

ATP03

The accuracy test involved positioning a small object (e.g. A4 paper) at various angles and distances relative to the sensor. Initially, when the pan angle matched the ultrasonic sensor reading, the water jet consistently missed due to a spatial offset between the sensor and nozzle. Applying a fixed pan offset of 30° corrected this misalignment.

Similarly, the tilt angle initially targeted the object's base, requiring a 15° tilt offset to aim at the object's center. With these offsets, the system reliably targeted the object's body, meeting ATP requirements.

It was also noted that the moderately flexible plastic tubing caused resistance and stress on the pan servo at wider angles. Future designs should use more flexible tubing to reduce mechanical stress and prevent gear stripping.

ATP05

Due to its prototype nature, several components did not meet Specification SP04, resulting in a failed ATP. Structural parts were 3D printed using PLA, a biodegradable, hydrophilic polymer lacking UV and water resistance—making it unsuitable for outdoor use. The prototype also included a basic perspex shelter, a plastic container for electronics, and clear tubing for wiring, which were adequate for testing but not for field deployment.

Future designs should incorporate a fully enclosed, weather-resistant shelter with rear clearance for full 180° jet panning. PETG, a UV-stabilized and impact-resistant material, is suggested for structures such as the pan and tilt mechanism. Electronics should be housed in an IP65-rated enclosure, and wiring routed through durable PVC conduit to ensure environmental protection and compliance.

ATP06

The 12V, 1A power supply constraint of the prototype was effectively managed through switching mechanisms integrated into the subsystem design. By controlling the pump's duty cycle using a control relay module such that it operated only when all servos—including the detection subsystem servo—were in an idle state, current distribution was successfully regulated within the system's power limitations.

Component	**Current (Average Range)**	**Mode**	**Power Management Strategy**
Water Pump	700–800 mA	Active during spray	Enabled only when servos are in idle mode.

Pan/Tilt + Detection Servos	150–200 mA each (working), 10 mA each (idle)	Idle during spray	Disabled during pump operation to manage current draw.
ESP32 MCU	∼100 mA	Always on	Low-power; always enabled.

Table 5.10: Current Characteristics and Power Management Strategy

ATP07

This test demonstrates that the deterrence subsystem outputs are both repeatable and reliable. While the subsystem did not fully meet the requirements outlined in ATP05, it exhibited accurate, effective, and consistent responses to target locations when tested. These results confirm the overall dependability and reliability of the response system.

5.3.2 Sensitivity Analysis

Parameter	**Values / Features**	**Effect**
Pan angle offset	15°, 30°, 45°	15°: Undershoots target, 30°: Hits target, 45°: Overshoots target.
Tilt angle offset	0°, 15°, 30°	0°: Sprays base of target, 15°: Sprays body of target, 30°: Sprays top of target or misses.
Servo gears	Plastic	Overuse susceptible to stripping.

Table 5.11: Effects of Key Features Sensitivity on Model Performance

5.4 Conclusions and Recommendations

The deterrence subsystem is a critical component of the overall system, directly influencing its operational effectiveness. Prototype testing demonstrated promising performance, particularly in meeting distance targets and achieving rapid responsiveness, indicating the current design provides a strong foundation for further development.

However, to transition from prototype to field-ready model, several modifications are necessary. All Acceptance Test Procedures must be successfully completed to verify reliability and specification compliance. It is recommended to replace the current pump with a higher-capacity unit capable of generating increased water pressure, extending the effective spray range to approximately 5–10 meters. The existing plastic tubing should also be substituted with more flexible piping to reduce mechanical load on the pan-tilt mechanism and allow greater angular movement without obstruction.

Furthermore, the system must be designed to comply with environmental protection standards suitable for outdoor deployment. Specifically, an IP65 (or higher) rating should be implemented to ensure resistance to dust and water ingress, thereby improving durability and operational lifespan under field conditions.

Chapter 6

GUI Subsystem (GMBTEN003)

6.1 Introduction

The predator detection system generates critical data that must be made accessible to users for in-depth examination and ensuing decision-making. To support this, the system must provide reliable mechanisms for data retrieval, visualisation through a graphical user interface (GUI), and transmission to external applications and/or gadgets. The GUI subsystem is the principal point of communication between researchers and the detection system. This enables efficient access, interaction, evaluation, and interpretation of the gathered data.

The development of this subsystem follows a structured design methodology. It begins with the identification of user needs and then proceeds to the formulation of functional requirements and detailed design specifications. These foundational elements advise decisions concerning hardware selection, front-end interface development, and overall system architecture.

To ensure the reliability and effectiveness of the interface, the design process incorporates a validation phase, during which comprehensive testing is performed. These tests inform the creation of an acceptance test procedure and are used to assess the system's usability, performance, and compliance with user expectations. This will ultimately confirm the soundness of the design decisions and the durability of the subsystem.

Upon completion of the design stage, the final deployment phase embeds the selected design components into a unified, competent, and functional GUI subsystem.

6.2 User Requirements

These outline the distinct expectations and functional needs that specialists have for the GUI component of the predator detection system. These requirements were elicited through direct researcher conversations, including face-to-face consultations conducted at the D-School with the stakeholders. The insights obtained during these interactions were consolidated and are presented below in Table 6.1. This set of requirements serves as the basis for the subsequent construction and application of a subsystem tailored to effectively support the needs of its target users.

Table 6.1: Consolidated List of GUI User Requirements

No.	User Requirement
UR01	**Ease of Use**: The GUI must be intuitive, straightforward to operate, and accessible to users with minimal training.
UR02	**Non-Intrusive Data Access**: Data collection processes must minimise disruption to the penguin colony, promoting usability and allowing researchers to access data remotely without physically entering the habitat.
UR03	**Image Download Functionality**: Given that image analysis will occur off-site and potentially at a later time, the application must support reliable downloading of captured screenshots to a user's devices.
UR04	**Data Management**: Include a mechanism to clear stored data from the local detection system once it has been compiled, thereby conserving storage space for future use.
UR05	**Visual Representation**: Accumulated data and images must be clearly and logically presented within the interface to support efficient review and interpretation.

6.3 Requirements Evaluation

Tables 6.2 and 6.3 provides a comprehensive analysis of the GUI subsystem requirements within the predator detection system. This analysis categorises the requirements into functional needs alongside their corresponding design specifications. The functional requirements were derived from a thorough examination of user demands to guarantee both effective operation and user-friendly interaction. Each functional requirement is accompanied by a detailed design specification that describes the implementation strategy intended to fulfill the stated need.

Table 6.2: Analysis (Part 1)

No.	Functional Requirements	Design Specifications
SP01	**Swift Feedback**: GUI must react to user inputs and information retrievals within a 10-second time frame.	To enhance performance and reduce latency, caching strategies and decoupled data loading will be utilised.
SP02	**Cross-Device Accessibility**: GUI should be compatible with a variety of device types.	A platform will be selected to warrant seamless usability over multiple device categories.
SP03	**Operational Condition**: The GUI must provide functionality to monitor the status of its framework.	Incorporate diagnostic features such as camera performance checks and battery level indicators.
SP04	**Information Accessing**: Pictures and data must be obtained remotely from the detection system.	A wireless communication protocol supporting transmission within the system environment must be chosen.

Table 6.3: Analysis (Part 2)

No.	Functional Requirements	Design Specifications
SP05	**Smooth Data Transmission**: Information and photos must be viewable for review at varied moments.	Download functionality will be integrated into GUI to facilitate data transfer to an external device.
SP06	**Understandable GUI**: The interface should be clean, straightforward, and easy to maneuver.	A simple design will be applied to promote an enjoyable experience with a user-friendly layout.
SP07	**Organized Data Presentation**: Fetched images should be shown in a clear, logical manner.	Data will be structured and presented to support efficient access and interpretation by the user.
SP08	**Memory Control**: Data storage must be regulated to prevent the SD card from overloading.	A feature allowing users to clear data from the SD card after successful download will be provided to maintain storage availability.
SP09	**Protection and Verification**: The system must enforce access control measures to ensure authorisation.	Network validation protocols will be implemented to safeguard system security.

6.4 Design Decisions

6.4.1 Micro-controller

A comparative evaluation of different microcontrollers was conducted to identify the most suitable candidate for the GUI of the predator detection system. Table 6.4 presents a detailed comparison of three microcontrollers (namely the ESP32-CAM, Raspberry Pi Zero W + Camera and Arduino Nicla Vision) based on key features relevant to this subsystem. This includes processing power, memory capacity, and communication interfaces. Following a comprehensive assessment, the ESP32-CAM emerged as the most viable option, as its specifications agree well with the established functional requirements and design constraints. Its dual-core processing unit satisfies the responsiveness criterion (SP01), while its onboard memory supports the system's data handling and storage requirements (SP04, SP05). Additionally, its integrated Wi-Fi, Bluetooth, and Ethernet capabilities enable broad accessibility (SP02) and facilitate secure and proficient data transmission (UR03, SP09).

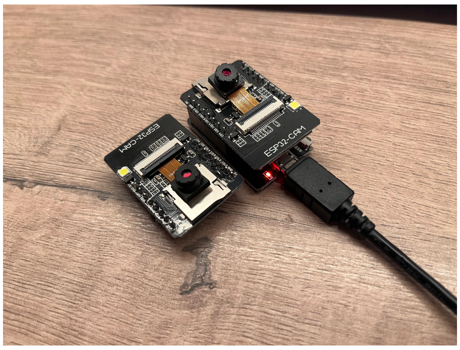


Figure 6.1: ESP32-Cam Microcontroller

Table 6.4: Micro-controller Evaluations

Micro-controller	**CPU**	**Memory**	**Network Access**
ESP32-CAM	Dual-core Xtensa 32-bit LX6 processor at 240 MHz: delivers robust processing capability for productive multitasking and user interface operations.	448 KB ROM, 520 KB SRAM, and 4 MB external PSRAM: satisfactory for software and data repository needs of the GUI.	Built-in Wi-Fi (802.11 b/g/n) and Bluetooth 4.2; supports UART, SPI, and I2C interfaces.
Raspberry Pi Zero W + Camera	Broadcom BCM2835, 1 GHz ARM11 single-core processor: offers ample power needed for processing and loading standard GUIs.	512 MB LPDDR2 SDRAM; expandable storage via MicroSD card slot: suitable for applications with moderate memory requirements.	Integrated 2.4 GHz 802.11 b/g/n Wi-Fi and Bluetooth 4.1; includes CSI camera connector and supports SPI and I2C interfaces.
Arduino Nicla Vision	Dual-core STM32H747AII6: ARM Cortex-M7 up to 480 MHz and Cortex-M4 up to 240 MHz, providing robust processing capabilities suitable for complex user interface tasks.	2 MB Flash, 1 MB RAM, and 16 MB QSPI Flash: ample memory for program storage and data handling requirements.	Integrated Wi-Fi and Bluetooth Low Energy 4.2 via Murata 1DX module; supports SPI and I2C interfaces.

6.4.2 GUI Homepage Design

This component is a crucial element of user interface development, acting as the intermediary between the end-users and the system's core functionalities. It directly influences how users interact with and perceive the system, making it a key factor in the overall user experience. Figure 6.2 illustrates the preliminary concept for the user interface, presented as a hand-drawn sketch depicting the various interface pages.

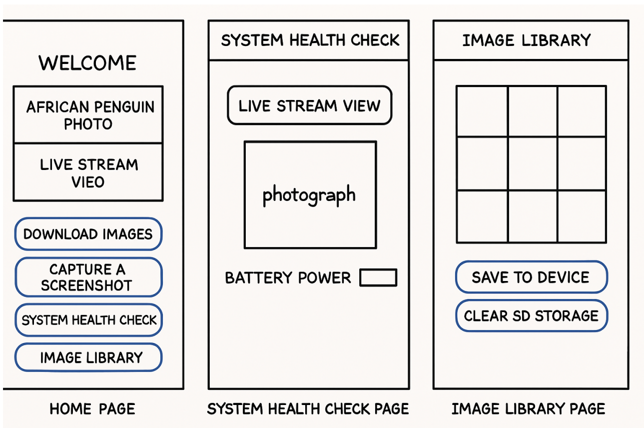


Figure 6.2: Preliminary Concept Design

The front-end design was guided by the requirements and specifications outlined in Sections 6.2 and 6.3. The focus was placed on creating a minimalist layout that prioritizes intuitive user interaction over visual aesthetics.

6.4.3 Model Infrastructure

This section outlines the architectural structure underlying the configuration and integration of the user interface subsystem. It covers the selection of development platforms, communication protocols, data management strategies, and protection mechanisms. Each element of the architecture is tailored to support seamless use, secure access, and reliable data handling, thereby improving the subsystem's overall performance and usability.

Framework Selection

Several platform options were considered for integrating the user interface with the ESP32-Cam. One possibility involved developing an OS-specific application for smartphones or tablets, enabling users to engage with and browse retrieved data. Yet, this approach would require device-specific customisation, which is impractical given the lack of information on the researcher's preferred device.

Cloud integration using platforms like Arduino Cloud, Google Cloud IoT, or Blynk IoT Cloud was another alternative, offering robust tools for data storage, access, and visualisation. Nonetheless, these services typically involve usage-based costs, making them unsuitable within the project's constraints.

A more viable solution lies in web-based applications. The ESP32-Cam is capable of hosting its own web server, enabling the creation of a browser-accessible interface. This allows users to remotely access and interact with the system via any device on the same network. Web applications offer broad compatibility, lower costs, easier scalability, and streamlined development. For this reason, a web-based interface was selected for this subsystem. To enhance performance, an asynchronous web server was implemented to handle HTTP requests simultaneously, improving the responsiveness and accuracy of data processing.

Network Protocol

The ESP32-Cam offers broad flexibility in terms of wireless communication options. For the predator detection system, the network protocol needed to be energy-efficient (to match the deterrence subsystem), capable of transferring sizeable data volumes (originating from the detection subsystem), and able to maintain a minimum effective range of approximately 1 meter (based on the system's expected detection radius). Table 6.5 outlines a comparison of several communication standards that were evaluated to identify the most suitable one.

Wi-Fi was ultimately selected as the communication method due to its compatibility with the project's core requirements. Within the Wi-Fi communication context, three client-server protocols were considered: HTTP Requests, Server-Sent Events (SSE), and WebSockets. SSE uses an HTTP connection to push updates from the server to the client, but it does not support two-way communication. WebSockets, on the other hand, enable real-time, bidirectional communication through persistent TCP connections, making them a strong candidate.

Despite these alternatives, HTTP requests were chosen for their simplicity, reliability, and full-duplex capability. They support data transmission both to and from the ESP32-Cam while acting as an access point. HTTP requests are also widely supported across platforms and easier to implement, making them a practical and effective solution for the subsystem's communication needs.

Table 6.5: Comparison of Wireless Network Protocols

Network Protocol	**Bit Rate**	**Power**	**Transmission Range**	**Notable Features**
ESP-NOW	Low–Medium	Low	Medium–Long	Efficient for quick, low-latency data exchanges.
LoRa	Very Low	Low	Very Long	Extremely long-distance communication.
Classic Bluetooth	Medium	Medium	Short	Optimized for continuous streaming.
Wi-Fi	High	High	Long	Supports multiple communication methods; best for large data transfers.
Bluetooth Low Energy	Low	Very Low	Short	Designed for ultra-low power operation.

IDE

The integrated development environment (IDE) refers to the suite of tools and programming languages employed during the implementation of the subsystem. The web application was developed using the Arduino IDE, incorporating a combination of C++, JavaScript, HTML, and CSS. More robust web development frameworks such as Django, Laravel, and Angular were intentionally excluded due to their relatively high memory consumption and the complexity of their associated libraries, which are unsuitable for the constrained resources of the ESP32 module. In contrast, the selected technologies offer lightweight solutions that facilitate direct integration with the ESP32's firmware.

Data Management

Data extraction from the Micro-SD card can be accomplished using either the `SD.h` or `SDD_$MCC.h` libraries, which operate via an SPI and the ESP32 SD/SDIO/MCC controller respectively. The `SD.h` library was chosen for this subsystem owing to its portable nature and targeted functionality. Since the subsystem primarily uses standard SD card operations, this library is adequate for the task. Additionally, the `SD.h` library enables clearing the Micro-SD card data, effectively freeing storage for new predator images.

Data is stored using the Serial Peripheral Interface Flash File System (SPIFFS), facilitating its acquisition and illustration within the web application. SPIFFS was preferred over other file systems such as LittleFs and FatFS due to its efficient file operations, ease of incorporation with web server applications, and straightforward execution. Moreover, the data stored in SPIFFS can be extracted and downloaded to the user's device, thereby completing the entire data transfer process.

Protection and Verification

The ESP32-Cam operates as a Wi-Fi access point, allowing nearby devices to connect directly to its dedicated network. To secure access to the web application and the associated data, the developer can configure a custom SSID and password for this network, which are disclosed only to authorised users. Once a user successfully connects to the network for the first time, their device typically retains the credentials, eliminating the need for re-entering the password during subsequent connections.

6.5 Final Design

This section outlines the final architecture of the subsystem, detailing the design of both the front-end and back-end, and describing how these components integrate with one another.

All the code for the graphical user interface can be found in this github repo:
https://github.com/tendygombs/EEE4113F_User_Interface_Subsystem_GMBTEN003

6.5.1 GUI Sub-Module Overview

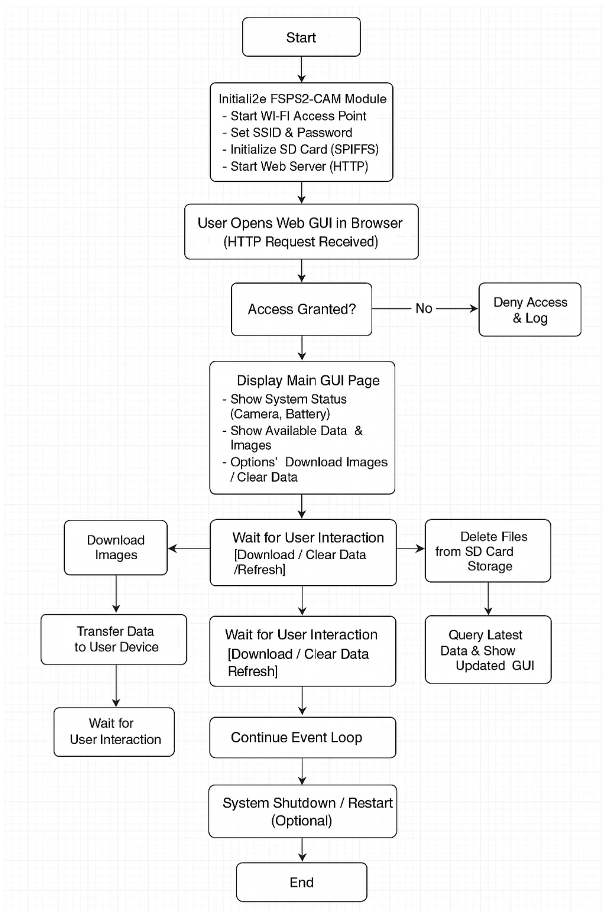


Figure 6.3: Block Diagram of User Interface

6.5.2 Front-end Code

The user interface of the web application is constructed directly within the C++ firmware as an embedded raw string, allowing for seamless integration between the ESP32-CAM hardware and the web interface. HTML and CSS are defined as string literals within the source code and served using the `WebServer` library. This approach enables dynamic generation of the homepage and other functional views, such as the image library and system health page.

The styling of the interface is handled through inline CSS within the HTML string, ensuring consistent formatting across different devices without requiring external stylesheets. The homepage layout includes a welcome header, live camera feed, and buttons that invoke JavaScript functions to trigger backend endpoints for capturing images, performing health checks, downloading stored files, and accessing the image library. This tight coupling between front-end presentation and back-end logic is essential to the ESP32-CAM's embedded design constraints and promotes efficient memory usage.

esp32cam_ui_homepage.ino

```
const char homepage_html[] PROGMEM = R"rawliteral(
<!DOCTYPE html>
<html>
<head>
  <title>ESP32-CAM Wildlife Monitor</title>
  <meta name="viewport" content="width=device-width, initial-scale=1">
  <style>
    body { background: #111; color: #eee; font-family: Arial, sans-serif; text-align: center; }
    h1 { color: #58f; margin-top: 10px; }
    p { font-size: 18px; }
    img { max-width: 90%; margin: 10px auto; border-radius: 12px; }
    button {
      display: block;
      width: 80%;
      margin: 10px auto;
      padding: 14px;
      font-size: 16px;
      background: #58f;
      color: white;
      border: none;
      border-radius: 8px;
    }
  </style>
</head>
```

Figure 6.4: HTML Code Snippet for Homepage

6.5.3 Back-end Code

The back-end of the subsystem is responsible for establishing wireless communication, managing data flow, and supporting the functionality of the web interface. The ESP32-CAM is configured as a Wi-Fi access point with a static IP address, enabling client devices to connect directly without requiring an external network. This configuration supports a local web server hosted on the ESP32, which handles all server-side operations.

The implementation relies on C++ in conjunction with libraries such as 'ESPAsyncWebServer' for handling asynchronous HTTP requests, and 'SPIFFS' for internal file system management. These libraries allow for efficient request handling and enable dynamic serving of content to the client. HTML and CSS resources are embedded as strings within the firmware and served via HTTP endpoints to render the web interface.

Captured images are stored on a Micro-SD card connected to the ESP32. The 'SD' and 'SPI' libraries are used to assist read-write operations to the external storage device. Retrieved data is often temporarily transferred to the internal file system (SPIFFS) before being served to connected clients. This layered approach to data management ensures that user interactions—such as requesting stored images or initiating new captures—are reliably handled through defined HTTP routes.

Overall, the back-end acts as a bridge between the user interface and the hardware's core functionalities, ensuring seamless communication and responsive operation.

6.5.4 Homepage Layout

Figure 5.3 presents the final configuration of the GUI subsystem. This integration merges the front-end and back-end components into a cohesive web-based platform capable of supporting data management operations.

Interactive features embedded within the front-end interface initiate defined back-end processes when engaged by the user. This interaction facilitates a flow of data from the client-facing interface to the server, where it is processed accordingly. Communication between these two layers is achieved via HTTP requests and responses, ensuring real-time feedback is delivered to the user interface in response to the corresponding operation.

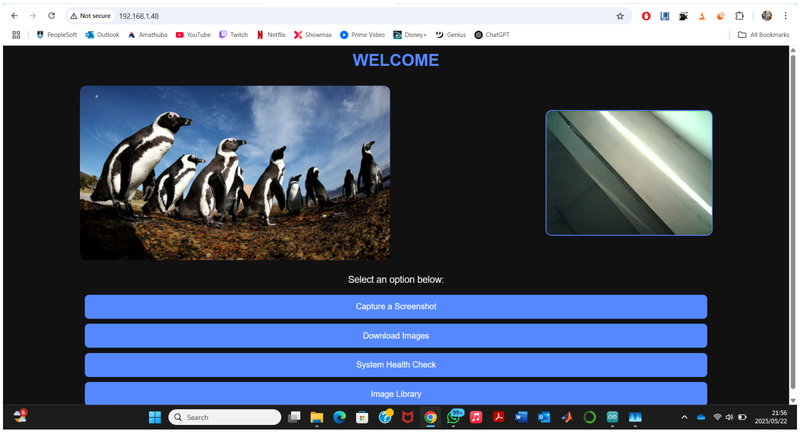


Figure 6.5: Final User Interface Desgin

6.6 Testing and Results

Testing constitutes a critical phase near the conclusion of the design cycle, providing valuable information regarding the subsystem's operational performance and user interaction. It serves to verify both the correctness and efficiency of the implementation. This section details the outcomes of four principal evaluations, aiming to analyse these findings and identify potential avenues for future enhancement.

6.6.1 Internet Speed Analysis

The purpose of this test was to assess the initialisation speed and responsiveness of the web server and associated application. Utilising web development diagnostic tools, multiple trials were performed, the results of which are summarized in Figure 6.4. Consistently, the server initialisation was observed to occur within approximately 100 milliseconds.

Nevertheless, challenges arose when the system attempted to launch the web application with a substantially increased image load. This issue underscores a limitation in handling large volumes of stored images simultaneously, indicating a need for further optimisation of the file storage and retrieval mechanisms.

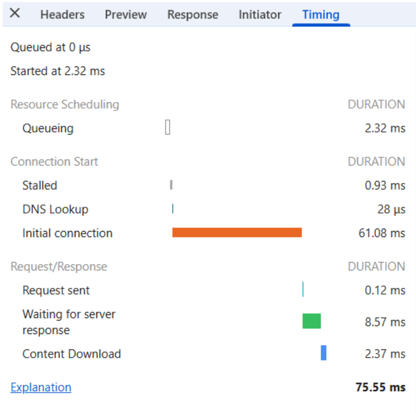


Figure 6.6: Network Bandwidth Diagnostics

6.6.2 File Transfer Assessment

This evaluation focused on the ability to retrieve image data from the file server and render it within the web application interface. The test was deemed unsuccessful, as images seldom loaded up on display for the user nor did monitoring through developer tools, as illustrated below show fast times.

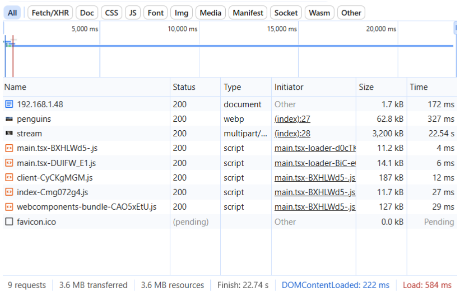


Figure 6.7: Data Transmission Testing

6.6.3 Accessibility Review

Figure 5.3 presents screenshots of the web application operating on Google Chrome via a laptop. Additionally, the application was tested on Safar and Internet Explorer across various devices, including laptops and tablets, to evaluate its responsiveness and compatibility with different browsers and hardware. The results were consistently positive, demonstrating that the design effectively adapts to varying screen sizes and orientations by maintaining content alignment at the center of the display.

6.6.4 Acceptance Test Procedure Evaluation

Acceptance Test Procedures (ATPs) are formulated based on the subsystem's specified requirements to evaluate its performance and verify whether the intended objectives have been fulfilled. For this user interface subsystem, User Acceptance Testing was selected as the primary evaluation method. The outcomes of this testing process are summarised in the table below.

Table 6.6: Summary of Acceptance Test Procedures and Outcomes

No.	**Description**	**Acceptance Criteria**	**Result**
ATP1	Ease of Use	The interface should be intuitive, allowing users to navigate and interpret information without difficulty.	**Passed**: Users present at demo were pleased with their experience.
ATP2	Non-Intrusive Data Access	Data should be accessible without physically disturbing the penguin or requiring the user to manually retrieve it.	**Passed**: Data was successfully accessed wirelessly using Wi-Fi and HTTP protocols from distances of up to 5 meters.
ATP3	Image Download Functionality	The application must allow users to download captured images for later analysis.	**Failed**: JPEG images cannot be successfully downloaded to the user's device via the web interface.
ATP4	Data Management	The interface should provide functionality to delete retrieved data from the SD card to conserve memory.	**Failed**: While implemented, the data-clearing feature is unreliable when processing larger data volumes.
ATP5	Visual Representation	Retrieved data and images should be clearly and logically presented on the interface.	**Passed**: Users at the demo found the layout visually appealing.
ATP6	Swift Feedback	System responses to user actions must occur within 10 seconds.	**Failed**: The interface occasionally exceeds the 10-second limit when handling requests.
ATP7	Cross-Device Accessibility	The interface must function consistently across various browsers and devices.	**Passed**: As confirmed during accessibility testing, the application is fully responsive across all tested platforms.
ATP8	Operational Condition	The system must support basic health diagnostics of other subsystems.	**Passed**: Includes features such as test image capture and battery status display.
ATP9	Protection and Verification	Authentication and security mechanisms must prevent unauthorised access.	**Passed**: Network access requires credentials, and the web interface is only accessible via its specific IP address.

The results of the acceptance testing indicate that the user interface subsystem largely satisfies its intended design requirements, with the majority of Acceptance Test Procedures (ATPs) being successfully met.

However, three key areas—Image Download Functionality (ATP3), Data Management (ATP4), and Swift Feedback (ATP6)—did not fully meet the established criteria. Although the user interface permits the initiation of screenshot capture requests and provides appropriate confirmation feedback, the images often fail to load in the image library. This failure is likely attributable to network limitations that impede successful data transmission.

The data management component also demonstrates inconsistent performance. Specifically, the system encounters difficulties when attempting to clear image files from the SD card, which may be the result of memory constraints or inefficiencies in the data handling algorithms. This limitation becomes particularly pronounced when managing large datasets, potentially leading to degraded system functionality. In the case of response latency, the system occasionally exceeds acceptable wait times for user actions, suggesting potential shortcomings in software responsiveness or temporary network congestion. Addressing these issues will require enhancements to algorithmic performance, more robust error handling mechanisms, and optimizations in network configuration.

Conversely, several aspects of the subsystem exhibited strong performance. The interface was deemed intuitive and easy to use (ATP1), and data retrieval via Wi-Fi HTTP protocols (ATP2) functioned effectively, enabling seamless data access while minimizing human interaction with the monitored environment. This is particularly beneficial in maintaining minimal disturbance to penguin habitats during data collection.

6.7 Conclusion

The user interface subsystem effectively serves as the communication conduit between the predator detection system and the end user, enabling researchers to interact with and retrieve data from the system with ease. Through systematic requirements analysis and iterative refinement, a user-oriented interface was developed to accommodate the operational demands of field researchers.

The subsystem employs a web-based application model to enable remote data access and efficient management across multiple device types. By leveraging the ESP32-CAM microcontroller's integrated web server functionality, the design prioritised clarity and usability, resulting in a streamlined front-end interface with intuitive navigation.

Wi-Fi-based communication, facilitated through HTTP protocols, was selected for its advantages in energy efficiency, extended range, and native compatibility with the ESP32-CAM platform. The interface is designed to operate with minimal resource consumption while integrating seamlessly with the embedded firmware of the microcontroller. Furthermore, access control was established through a credential-based authentication mechanism to ensure secure usage.

Comprehensive testing confirmed that the subsystem is dependable, performant, and secure. Its design aligns with the practical requirements, supporting uninterrupted system operation and facilitating reliable data acquisition. This user interface enables effective, minimally invasive wildlife monitoring, particularly suited for studying the African penguins and aiding them in protection against predators.

Chapter 7

Conclusion

The purpose of this project was to design and build a detection and deterrence system used to protect penguin colonies in the De Hoop Nature Reserve from predators, using non-harmful methods. Additionally, it aimed to provide a wireless form of communication to enable off-site analysis of the environment. This report began with identifying a problem statement and analyzing the issue at hand, providing an introduction to each subsection, forewording the technical explanations and design decisions to be explored. The literature review was followed in Chapter 3, giving an in-depth analysis of research into similar topics, creating a broader understanding of detection and deterrence systems . Understanding previous works assisted us in gaining insight, inspiring ideas, and creating a comprehensive understanding of what needs to be done and possible ways to meet the problem statement.

The bulk of the work for this project followed next, in Chapter 4 , where the successful development of a radar-based detection accurately identified animal movement and located threats in real time. Using an ultrasonic sensor on a servo motor, the system performed continuous sweeps and sent distance and angle data wirelessly via UDP to a radar GUI. This data was also shared with the deterrence system, enabling coordinated, off-site threat detection and response.

Following on, Chapter 5 presented the development of a well-integrated and responsive deterrence mechanism, effectively complementing the detection subsystem. This integration was validated through successful acceptance testing, demonstrating the performance of a high-pressure water jet system designed to deter intruding animals. The system utilized rotational actuation to accurately track target locations based on real-time sensing data.

Chapter 6 focused on developing a user-friendly, accessible, and responsive GUI to bridge communication between all the subsystems. The GUI was implemented as a browser-accessible web application that enabled wireless data retrieval, system monitoring, and live visual feedback. Key features included the ability to capture and download images, view system health metrics such as battery voltage, and access a live camera feed for visual confirmation of threats.

In summary, the project achieved the goals that were set out by designing and successfully demonstrating an ultrasonic radar system to detect potential threats in the environment. The Radar data is accurately sent to the deterrence mechanism, which uses a coordinate system to locate threats. Deterrence is achieved through non-harmful high-pressure water jets aimed at the threat's position. The system allows off-site visualization of detected threats via the radar interface, and a real-time surveillance camera feed can be accessed through a mobile device to visually confirm threats.

Chapter 8

Bill Of Materials

Component Name	**Quantity**	**Unit Price (ZAR)**	**Total (ZAR)**
HC-SR04 Ultrasonic Sensor	1	75.00	75.00
SG90 Servo Motor	1	32.00	32.00
Recycled Glass Jar	1	0.00	0.00
PLA filament for Sensor Housing	1	11.27	11.27
Female/Male Connector Wiring	1	35.00	35.00
Perfboard (Perepex)	1	70.00	70.00
ESP32	1	188.00	188.00
Veroboard	1	20.00	20.00
Buck Converter (HDK)	1	13.00	13.00
ESP32 Cam	1	114.00	114.00
ESP32 CAM Baseboard	1	40.00	40.00
5V 1-Channel Relay Module	1	24.00	24.00
SG90 Servo Motor	2	32.00	64.00
ZKSJ DC40 Pump	1	300.00	300.00
HKD Relay Board 1Ch 12V	1	29.00	29.00
PLA Filament for Deterrent	1	16.74	16.74
10mm Clear Plastic Tubing	1	19.32	19.32
Irrigation Nozzle	1	30.00	30.00
1k Resistor	2	0.80	1.60
Total			**1054.92**

Table 8.1: Bill of Materials for Project

Chapter 9

GA Table

Subsystem:	Detection
Student Number:	MCHJOH015

GA	Requirement	Justification
3	Engineering Design	Section(4.3 , 4.4) , pages(13,15,16,17,18,19)
7	Sustainability and Impact of Engineering Activity	D-School, Section(4.3 , 4.4 , 4.5) , page(14,15,18,19,21,22,23)
8	Individual, Team and Multi-disciplinary Working	See Teams group for meeting minutes
10	Engineering Professionalism	All submission activities met including final report and presentation

Table 9.1: Mapping of Graduate Attributes to Activities

Subsystem:	Deterrence
Student Number:	CRSKAT005

GA	Requirement	Justification
3	Engineering Design	Section 5.2, pages 26-32
7	Sustainability and Impact of Engineering Activity	D-School, Section 5, pages 24-34
8	Individual, Team and Multi-disciplinary Working	See Teams group for meeting minutes
10	Engineering Professionalism	All submission activities met including final report and presentation

Table 9.2: Mapping of Graduate Attributes to Activities

Subsystem:	Graphic User Interface
Student Number:	GMBTEN003

GA	Requirement	Justification
3	Engineering Design	Section 6.4, 6.5, pages 38-44
7	Sustainability and Impact of Engineering Activity	D-School, Section 6, pages 36-47
8	Individual, Team and Multi-disciplinary Working	See Teams group for meeting minutes
10	Engineering Professionalism	All submission activities met including final report and presentation

Table 9.3: Mapping of Graduate Attributes to Activities

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