Automated Sprinkler-Based Predator Deterrent System

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Abstract

Penguins are ocean health indicators. However, the conservation of African penguins is increasingly threatened by predation from terrestrial predators such as honey badgers and leopards, as existing predator deterrent systems have become less effective. Predators quickly adapt to these measures and become habituated due to their lack of lasting impact. By leveraging on the limitations of the existing predator deterrent system, the project designed and developed a non-lethal, cost-effective, and low-power consumption predator deterrent solution.

The proposed solution will be integrated with an electric fence to reinforce penguin protection against predators. It uses motion sensors, solar-powered components, and remote monitoring capabilities to operate autonomously with minimal human intervention. The system provides a non-lethal and humane method of deterring predators, ensures environmental sustainability, and enhances the overall effectiveness of predator deterrent systems. The system's design focused on creating a hostile environment for predators without causing harm, thereby supporting the survival and recovery of African penguin populations. This report provides a comprehensive review of existing deterrent methods, evaluates their effectiveness and limitations, and proposes a hybrid solution tailored to the specific needs of African penguin conservation. Through this approach, the project aims to contribute significantly to the protection and conservation of African penguins, offering a model for similar efforts in other regions and with other species.

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PIR Passive Infrared

Chapter 1

Introduction

1.1 Background and Motivation

African penguins have been classified as endangered species since 1984, and with a constant decline in population and breeding pairs over the years, they are expected to extinction by 2035 if no interventions are made [1]. The population decline is caused by complicated and interconnected factors. Among them is the direct competition imposed by commercial fishing, resulting in a food crisis. Secondly, climate change has led to changes in ocean temperature, making prey hunting much more challenging. Lastly, terrestrial predators such as honey badgers and leopards have emerged as a serious threat to mainland colonies due to their strength, ingenuity, and determination, frequently overcoming physical barriers that were once considered impenetrable.

After a presentation by **Christina Hagen**, Pamela Isdell Fellow of Penguin Conservation at BirdLife South Africa, highlighting how terrestrial predators breached an electric fence and killed 33 penguins at Boulders Penguin Colony, this project has developed an automated sprinkler-based deterrent system. The system is made up of two subsystems, namely, detection and deterrent subsystems.

To address challenges that traditional deterrent systems face, the system is impactful yet non-lethal. The detection subsystem uses Passive Infrared (PIR) motion sensor to detect movement. Once movement has been confirmed, the ESP32-CAM integrated with image recognition classifies the animal as a target (Predator) or non-target (Penguins or human beings). A signal is sent to activate the deterrent subsystem if a predator is detected. The deterrent subsystem remains activated until the predator has been chased away or the timer has elapsed.

1.2 Objectives

Based on the aforementioned challenges, the primary objectives of this report are therefore to:

- Protect African penguins at the Boulders Penguin Colony from predators using technology.
- Design a non-lethal predator deterrent system.
- Design a weather-resistant solution capable of enduring the extreme environmental conditions of the colony.
- Develop an autonomous system that minimises human intervention to prevent disturbances to penguins while ensuring effective monitoring and protection against predators.

- Develop a cost-effective, easy-to-install and relocate low-power consumption, and minimal data usage solution.

1.3 Scope and Limitations

This project concerns designing and developing a fully autonomous predator deterrent system to protect African penguins at Boulders Penguin Colony. While African penguins remain threatened by many factors, the project's scope is limited to predators, specifically honey badgers and leopards. Budget and power consumption constraints impose further limitations.

1.4 Plan of Development

The project report has been structured systematically to provide a comprehensive understanding to the readers as follows:

- Chapter 1 offers a comprehensive overview of the report, outlining its background and motivation, objectives, scope and limitations, and overall structure.
- Chapter 2, literature review, evaluates existing predator deterrent systems, conducting a critical analysis of their limitations and assessing technological advancements. It then identifies research gaps to provide a well-founded conclusion on potential areas for further investigation and improvement.
- Chapter 3, outlines the design and development of the detection subsystem. This section further provides subsystem integration and interfacing.
- Chapter 4, outlines the design and development of the deterrent subsystem.
- Chapter 5 concludes the report based on the system performance.

Chapter 2

Literature Review

> If you wish to make an apple pie from scratch, you must first invent the universe.
>
> —*Carl Sagan*

2.1 Background to Predator Deterrent Systems

Penguin colonies, particularly those situated in mainland areas, face escalating threats from terrestrial predators such as honey badgers, leopards, and other carnivorous species [2]. These predators pose a significant risk to penguin populations by preying on eggs, chicks, and adult birds, especially during breeding seasons when penguins aggregate in large numbers on land, rendering their offspring particularly vulnerable to opportunistic attacks. Penguins are vital to marine ecosystems [3], serving as top predators that help maintain the balance of food webs and contributing to nutrient cycling through their guano, which underscores the urgent need for their conservation.

However, protecting these colonies presents substantial challenges due to their location in remote and harsh environments, such as coastal regions with limited human presence. These areas are often characterized by extreme weather conditions—including strong winds, low temperatures, and rough seas—that complicate the deployment and maintenance of protective measures [4]. Traditional predator control methods, such as trapping or culling, are not only ethically contentious but also impractical in such isolated settings, where both the preservation of native predator species and logistical constraints must be considered [2]. Consequently, there is a critical demand for effective, non-lethal predator deterrent systems that can safeguard penguin colonies while minimizing harm to predators and preserving ecosystem integrity.

Predator deterrent systems encompass a variety of strategies and technologies designed to prevent or mitigate predation by discouraging predators from approaching or attacking vulnerable species. These systems play an essential role in wildlife conservation and management, protecting both ecological assets and human interests, such as livestock and crops [5]. Deterrents are typically classified by the stimuli they utilise, including:

- **Auditory deterrents:** These employ sounds—such as gas exploders, sirens, or recordings of predator distress calls—to repel predators.
- **Visual deterrents:** These rely on visual cues like flashing lights, reflective materials, or effigies to intimidate or scare predators away.

- **Physical barriers:** Structures such as fences or nets physically block predator access to protected areas.
- **Bioacoustic deterrents:** These use specific sounds, often mimicking predator calls or prey distress signals, to alter predator behavior.

The effectiveness of these methods varies depending on factors such as predator species, environmental conditions, and implementation specifics, with habituation posing a common challenge that can diminish long-term success [5]. As a result, combining multiple deterrent approaches or developing adaptive systems may be necessary to ensure sustained protection. Key studies, such as Gilsdorf et al. [5], have reviewed the application of frightening devices in wildlife damage management, offering valuable insights into the mechanisms, efficacy, and limitations of various deterrent types. Understanding how these systems can be tailored to the unique challenges of penguin conservation is essential for devising sustainable and ethical solutions to protect these ecologically significant seabirds in their natural habitats [2].

2.2 Existing Deterrent Techniques

This section explores the technological advancements and existing methodologies employed in predator deterrent systems. The focus will be on understanding various deterrent strategies' effectiveness, limitations, and practical applications. A comprehensive review of existing research will present a detailed overview of the current landscape of predator deterrent technologies.

The examination will cover several categories, including auditory and bioacoustic deterrents, visual deterrents, physical barrier deterrents, and guard animals. Each subsection will highlight key findings, innovations, and challenges associated with these methods, thereby establishing a solid foundation for developing an effective deterrent system tailored to the needs of African penguins. Furthermore, this review will identify gaps in the current research and offer recommendations for improving the effectiveness and sustainability of predator deterrent systems.

2.2.1 Auditory Deterrents:

Auditory deterrents use sound to create an environment that feels threatening to predators, keeping them away from protected areas. These methods include gas exploders, bioacoustic alarms, and recorded predator calls. Gas exploders emit loud sounds at intervals, mimicking gunshots to scare off predators [6]. While effective in the short term at reducing predation on livestock and crops, their effectiveness may diminish as animals become accustomed to the noise [6]. Bioacoustic alarms play recorded distress or predator calls to signal danger. For instance, distress calls of prey can alert predators, causing them to flee. Research shows these alarms can effectively deter birds and mammals from agricultural areas [5]. Recorded predator calls can also be used to simulate a predator's presence, protecting livestock from species like wolves and coyotes. However, the long-term effectiveness of auditory deterrents can be limited as animals may habituate to the sounds.

To enhance effectiveness, auditory deterrents should be combined with visual deterrents or physical barriers. Ultimately, while auditory deterrents offer a non-lethal, environmentally friendly way to protect livestock and crops, they work best as part of a broader pest management strategy.

2.2.2 Visual Deterrents

Visual deterrents are that help keep predators at bay by creating an environment that feels threatening or uncomfortable for them. Some common examples include reflective tape, scarecrows, and strobe lights [5]. Reflective tape, for instance, uses flashes of light to mimic danger, which can trigger an instinctive flight response in animals. Research has shown that this method can be quite effective in deterring birds and some mammals; the sudden reflections can startle and confuse them [7]. However, it's important to note that the effectiveness of reflective tape can vary by species and the situation in which it's used. Some animals may quickly get used to the reflections and, over time, ignore them [8].

Scarecrows have been around for ages and are designed to look like humans or predators, which helps scare away birds and other animals. Studies suggest that scarecrows can be effective, especially if they are moved frequently, so animals do not get too comfortable [9]. However, animals that are used to seeing people might eventually recognize that a scarecrow isn't a real threat and return to the area [10]. Another option is strobe lights, which flash bright bursts of light. These can disrupt animals' normal behavior and encourage them to avoid certain places. While strobe lights can work well to repel different species, their success often depends on their placement and how the specific animals behave [11].

Despite their initial success, one of the challenges with visual deterrents is that animals can become habituated to them, meaning they get used to the stimuli and don't view them as threats anymore. This is why it's often best to use visual deterrents alongside other methods—like sounds or physical barriers—to boost their effectiveness. By combining different strategies, we can create a more dynamic environment that keeps animals guessing and less likely to overcome those deterrents [12].

2.2.3 Physical Barriers

Physical barriers like fences and nets are often employed to protect penguin colonies from predators [2]. Fences can be built around nesting areas to keep out ground predators such as honey badgers and leopards, while nets overhead can help fend off aerial threats. Research indicates that these barriers can significantly reduce predation rates [8], making them a suitable option for conserving these vulnerable species. However, the success of such measures greatly depends on their design, construction quality, and ongoing maintenance.

Despite their effectiveness, there are notable challenges tied to the use of physical barriers. The installation and upkeep of these structures can be quite costly, requiring high-quality materials and skilled labor [13]. Regular maintenance is also essential, as weather conditions and environmental wear can compromise their integrity over time. In addition, barriers can inadvertently affect the natural behavior and movement of penguins, potentially disrupting their activities and habitat use. Nonetheless, when combined with other deterrent strategies, physical barriers remain a crucial element in the conservation of penguin colonies, despite these challenges.

2.2.4 Guard Animals

Guard animals, particularly dogs, are highly effective in safeguarding livestock from predators [8]. They are trained to remain close to the herd, using their presence and behaviors to discourage threats.

Livestock guardian dogs, such as the Great Pyrenees, are well-regarded for their vigilance and readiness to confront predators directly [14]. Similarly, llamas serve an important role; they are social and alert creatures that excel at detecting danger and raising the alarm when predators are near [14]. Using guard animals has proven to be a successful and humane strategy for protecting livestock from various threats, including coyotes, foxes, and bears.

Adapting the use of guard animals for penguin conservation presents a unique set of challenges and opportunities. While the concept of using guard animals to protect penguin colonies is promising, it requires careful consideration of the specific needs and behaviours of both the penguins and the guard animals. For instance, the presence of dogs or llamas in penguin colonies must be managed to ensure that the guard animals do not inadvertently harm the penguins or disrupt their natural behaviour [6]. Additionally, training guard animals to recognize and respond to specific threats to penguins, such as honey badgers and leopards, is essential for their effectiveness. Despite these challenges, the use of guard animals could provide an innovative and sustainable solution for protecting penguin colonies, particularly when integrated with other conservation strategies.

2.3 Comparison of Advanced Technological Techniques

Mishra and Yadav [15] compare advanced technological techniques for detecting and repelling predators, as illustrated in Table 1. All techniques demonstrated effectiveness ranging from a minimum of 87% to a maximum of 96%. However, a limitation is that most of these techniques are designed for agricultural purposes and require constant human intervention.

Table 2.1: Comparison of advanced technological techniques

Technique	**Detection Accuracy(%)**
Embedded Edge-AI-based Intelligent Animal Repelling System (EEAIRS)	87
Automated Virtual Elephant Fence (AVEF)	95
Peacock Repellent Technique (PRT)	88
Crop Protection System (CPS)	92
Agricultural Intrusion Detection	94
Explainable Deep Vision System (EDVS)	85
IoT-based Embedded System for human-wildlife conflict	92
Enhanced Animal Migration Optimization Algorithm (IAMOA)	85
Intelligent Framework for cattle risk identification	96

2.3.1 Limitations of Deterrent Methods

Habituation

One of the primary limitations of both auditory and visual deterrents is habituation. Over time, predators may become accustomed to the stimuli and no longer perceive them as threats, reducing their long-term effectiveness [5, 12]. To mitigate habituation, it is recommended to use a combination of deterrent methods and periodically change the stimuli [8].

Environmental Constraints

Environmental factors, such as weather conditions and terrain, can affect the effectiveness of deterrent methods. Severe weather can damage physical barriers, which would then require regular maintenance and repairs. Furthermore, the surrounding environment can influence the effectiveness and placement of auditory and visual deterrents [16].

Ethical Considerations

Non-lethal deterrent methods are preferred for ethical reasons, as they protect both target species and predators without causing harm [12]. It's crucial to ensure these methods do not unintentionally affect non-target species or disrupt natural behaviors, balancing effective predator control with ethical considerations for sustainable wildlife management [5].

While the total elimination of damage may be impossible [5], frightening devices and combinations of various deterrent methods have proven useful in reducing wildlife damage. Each method, including auditory deterrents, visual deterrents, physical barriers, and guard animals, has its limitations, such as habituation, environmental constraints, and ethical considerations. However, combining multiple deterrent strategies and considering these factors can enhance the overall effectiveness and sustainability of predator deterrent systems.

2.4 Relevance to Current Work

The works presented demonstrate a variety of techniques aimed at deterring predators. However, it is noted that the primary focus of the study will be on a penguin habitat, which may affect the effectiveness of the predator deterrent methods and will mainly concentrate on deterring honey badgers and leopards.

Auditory deterrents, such as gas exploders and bioacoustic alarms, have proven effective in reducing predator encounters in agricultural settings [6]. However, their suitability for a penguin habitat remains uncertain. Honey badgers and leopards primarily rely on stealth rather than auditory cues to locate prey, which makes habituation to sound-based deterrents a potential limitation. Furthermore, penguins are highly vocal animals, and the introduction of artificial sounds may disrupt their natural communication and breeding behaviours, raising concerns about their overall efficacy in this specific context.

Visual deterrents, such as reflective tape, scarecrows, and strobe lights, are commonly used in wildlife management [5]. These deterrents can be effective in startling predators, but their success depends on species-specific responses. In the case of penguin colonies, honey badgers and leopards are nocturnal predators, making the use of strobe lights potentially beneficial in deterring them [11]. However, reflective surfaces and scarecrows may have limited effectiveness, as these predators rely more on scent and stealth rather than visual cues. Moreover, the risk of penguins habituating to visual deterrents necessitates further research into unpredictable deterrent mechanisms

Physical barriers, such as fencing and nets, have been used to protect vulnerable wildlife from predation [2]. Additionally, fencing can be an effective method for keeping out ground-based predators like honey badgers. However, the implementation of such barriers presents challenges, including cost, maintenance, and potential disruption to penguin movement patterns [13]. Additionally, barriers may be ineffective against leopards, which can climb fences, necessitating additional deterrent strategies to complement physical enclosures.

The use of guard animals, particularly livestock guardian dogs and llamas, has shown success in agricultural settings by deterring predators through their presence and defensive behaviour [14]. While this could be adapted for predator deterring, the introduction of large mammals into penguin colonies may bring unforeseen consequences. For instance, careful selection and training would be required to ensure that guard animals do not disturb nesting penguins or become a source of stress within the colony.

Advanced technological solutions, such as embedded AI-based deterrents and IoT-based wildlife monitoring, have demonstrated high detection accuracy in agricultural environments [15]. However, these technologies often require human intervention and infrastructure, which may be impractical for remote or protected penguin habitats. Additionally, the long-term sustainability and impact on predator-prey dynamics remain underexplored.

While existing deterrent methods offer valuable insights for managing predators, their direct application to penguin conservation needs adaptation. It is crucial to evaluate the effectiveness of auditory, visual, physical, and biological deterrents within the specific ecological and behavioural context of African penguins. To develop a sustainable and effective predator deterrent system for penguin colonies, it is essential to integrate multiple deterrent strategies tailored to address the unique threats posed by honey badgers and leopards.

2.5 Research Gap and Critical Thinking Analysis

Despite advances in predator deterrent technologies, several research gaps remain when considering their application to penguin conservation. One of them is the limited focus on non-traditional predators such as honey badgers and leopards. Most deterrent techniques have been designed for canines and avian predators, leaving uncertainties about their effectiveness against different species with different behavioural patterns [5]. More research is needed to understand how these specific predators interact with deterrent systems in coastal environments in which penguins reside.

In addition, habituation presents a significant challenge. Many reviewed auditory and visual deterrents suffer from diminishing effectiveness over time as predators become accustomed to them [12]. Adaptive deterrent systems that use randomised patterns or multisensory stimuli could help mitigate this issue. Investigating predator-specific responses to various deterrents and identifying optimal strategies for maintaining long-term effectiveness are essential.

Another critical research gap involves the ecological and ethical implications of implementing deterrent systems in penguin habitats. Although physical barriers and guard animals offer promising solutions, their potential impact on penguin behaviour and habitat use has not been thoroughly studied. Excessive fencing may limit penguin mobility and access to breeding sites, while the introduction of guard animals could lead to unintended stress or disruptions within the colony. Additionally, it is widely preferred to use non-lethal means of deterring predators such as leopards [12].

Moreover, the environmental constraints of coastal regions must be considered when designing and deploying deterrent systems. Factors such as wind, saltwater corrosion, and extreme weather conditions can affect the durability and functionality of deterrent technologies. Many existing deterrent methods have been developed for agricultural settings [5], where environmental factors are more predictable and manageable. Research is needed to adapt these technologies to withstand the harsh conditions of penguin habitats and ensure long-term viability.

Finally, fostering interdisciplinary collaboration is essential for refining and implementing effective deterrent strategies. Combining studies on ecology and animal behaviour will be crucial in creating solutions tailored to penguin conservation. More research should investigate innovative approaches, such as AI-driven monitoring systems, adaptive deterrent algorithms, and habitat modifications that reduce predator encounters while maintaining the natural integrity of penguin colonies [15].

By addressing these research gaps and leveraging critical thinking in the development of predator deterrent strategies, it is possible to create more effective, sustainable, and ethically sound solutions for protecting African penguin populations from predation threats.

2.6 Conclusion

Investigating various predator deterrent systems and their potential to protect African penguin colonies from terrestrial predators, such as honey badgers and leopards. The study highlights a range of methods—auditory deterrents (e.g., gas exploders, bioacoustics alarms), visual deterrents (e.g., reflective tape, strobe lights), physical barriers (e.g., fences, nets), and guard animals (e.g., dogs, llamas)—each with unique strengths and weaknesses.

Notably, auditory and visual deterrents are initially effective but often lose efficacy due to predator habituation as discussed in [5]. Physical barriers offer strong protection but are costly, require ongoing maintenance, and may inadvertently influence penguin behaviour. Guard animals can be effective but need careful management to avoid disrupting the penguins themselves. These findings illustrate the challenges of adapting deterrent systems to the specific environmental conditions of penguin habitats.

A significant solution is the potential of multi-sensory and adaptive approaches as in [15]. By combining auditory, visual, and physical deterrents systems can overwhelm predator senses and reduce habituation, making them more effective. However, the review identifies notable research gaps. Most existing deterrent methods are designed for agricultural or livestock protection, not the coastal ecosystems where penguins reside. Further studies are essential to assess how honey badgers and leopards respond to deterrents in these unique settings and to devise methods such as randomised stimuli or adaptive algorithms that mitigate habituation.

Emerging technologies present exciting opportunities. Innovations like AI-driven monitoring systems and the use of machine learning could provide real-time predator tracking, triggering dynamic responses such as drones or strobe lights. These technologies must be further tested to ensure they do not disturb penguins or harm non-target species while also addressing challenges like durability in harsh coastal conditions.

Chapter 3

Predator Detection - STWNAN001

3.1 Introduction

This chapter presents the design and development of the Predator Detection subsystem, a key component in the Automated Sprinkler-Based Predator Deterrent System Design. This subsystem is responsible for detecting motion in the environment, capturing an image when potential movement is identified, and classifying the object to determine if it is a threat to the penguin colony, specifically targeting predators such as leopards and honey badgers.

3.2 Requirements and Specifications

3.2.1 User Requirements

The stakeholder, Christina Hagen, a Pamela Isdell Fellow of Penguin Conservation in Birdlife South Africa, outlined the following as the requirements for the detection subsystem.

Table 3.1: User Requirements

URID	**User Requirement**
UR1	Detect when animals are nearby.
UR2	Must not harm the predator being deterred.
UR3	Only respond to specific predators (e.g., leopard, badger).
UR4	Operate in low-light outdoor environments.
UR5	Low-cost, reliable hardware.

3.2.2 Requirements Analysis

Based on the user requirements, the following functional requirements (FR), specifications (SP), and Acceptance Test Procedures (ATP) were developed. The specifications establish a standard for the subsystem, while the ATPs will be used to evaluate whether the proposed solution meets these standards.

Table 3.2: Functional Requirements

FRID	Functional Requirement
FR-1	Control the system using a microcontroller.
FR-2	Detect motion using a sensor-based method.
FR-3	Capture and transmit an image of the detected object.
FR-4	Classify detected objects using machine learning on a web server.
FR-5	Trigger the deterrent system if a known predator is identified.
FR-6	Use power-saving techniques to limit the use of power.
FR-7	Use low-cost components suitable for field deployment.

Table 3.3: Specification to Requirement and Test Traceability Matrix

SPID	Specification	FRID	ATPID
SP-1	Use the ESP32-CAM Module operating at 5.0V	FR-1	ATP-1
SP-2	Use the HC-SR501 PIR sensor to detect motion at distances up to 7 meters	FR-2	ATP-2
SP-3	Use ESP32-CAM to process sensor data and capture images	FR-2, FR-3	ATP-3
SP-4	Use the OV2640 camera module to capture images	FR-3	ATP-4
SP-5	Send captured images via Wi-Fi POST to web server for classification	FR-3	ATP-5
SP-6	Classification must distinguish between human, honey badger, and leopard with >80% accuracy	FR-4	ATP-6
SP-7	Use a 3.3V GPIO output to trigger the sprinkler system	FR-5	ATP-7
SP-8	ESP32-CAM should use deep sleep mode when idle to conserve power	FR-6	ATP-8
SP-9	The system should cost less than R750 per deployed unit	FR-7	ATP-9

Table 3.4: Acceptance Test Procedures

ATPID	Test Procedure	Success Criteria
ATP-1	Connect ESP32-CAM to a regulated 5V power supply. Flash a basic blink/test sketch. Observe LED and measure current.	ESP32 powers up correctly; red LED blinks and current draw is within safe limits.
ATP-2	Power the HC-SR501 PIR sensor with 5V and GND. Connect OUT pin to GPIO on ESP32-CAM. Monitor Serial output on motion.	Console prints "Motion detected!" when a person moves within 7 meters.
ATP-3	Flash code to ESP32-CAM that waits for PIR signal and then captures an image. Move in front of sensor and observe Serial response.	Image capture occurs only when PIR triggers HIGH.
ATP-4	Test OV2640 camera image capture by running capture-only code.	Image captured successfully with camera.
ATP-5	Send an image to web server endpoint `/classify` using ESP32-CAM. Confirm receipt and server reply.	Server returns classification result (e.g., "leopard").
ATP-6	Present known photos or physical representations of each class (leopard, badger, human). Record predictions.	Model correctly classifies $\geq$80% of test images.
ATP-7	Connect GPIO pin to relay/LED. Trigger classification of a known predator. Monitor pin state.	GPIO goes HIGH for at least 3 seconds when a threat is identified.
ATP-8	Enable deep sleep mode after inactivity. Measure current draw and verify wakeup on PIR input.	ESP32 enters sleep mode (low current $<$ 1 mA), then wakes up on motion.
ATP-9	Add up all hardware components used (ESP32-CAM, PIR, relay, power module, etc.). Evaluate cost with reference to local prices.	Total cost $\leq$ R750 per unit.

3.3 Design Choices

3.3.1 Microcontroller

This subsystem requires a microcontroller to act as the central processing unit. The Raspberry Pi Pico, ESP32-CAM, and Arduino Uno R3 were the primary candidates considered. Key factors influencing the decision included cost, clock speed, integrated Wi-Fi, and the availability of a built-in camera.

Table 3.5: Microcontroller Comparison [17], [18], [19]

Feature	ESP32-CAM	Raspberry Pi Pico	Arduino Uno R3
Price	R182.00	R154.00	R155.00
In-Built Camera	Yes	No	No
Wi-Fi	Yes	Yes	No
Clock Speed	240 MHz	133 MHz	16 MHz

The ESP32-CAM has been selected as the ideal microcontroller for this project due to its advantageous combination of affordability, integrated features, and performance.

While the Raspberry Pi Pico and Arduino Uno R3 are similarly priced (R154.00 and R155.00, respectively), the ESP32-CAM offers substantial benefits for only slightly more at R182.00. It includes a built-in OV2640 camera module, eliminating the need for an external camera and simplifying the hardware design.

Moreover, the ESP32-CAM includes native Wi-Fi capability, essential for transmitting images to the server. In contrast, the Arduino Uno R3 lacks this feature entirely, and the Raspberry Pi Pico requires an additional module to gain Wi-Fi connectivity.

In terms of processing power, the ESP32-CAM's 240 MHz clock speed significantly exceeds that of the Raspberry Pi Pico (133 MHz) and the Arduino Uno R3 (16 MHz), allowing for faster image processing and better performance in handling network communications.

Overall, these advantages make the ESP32-CAM the most cost-effective and technically suitable microcontroller for the implementation of the detection and classification subsystem in the predator deterrent system.

3.3.2 Sensor

The Passive Infrared (PIR) sensor was chosen for motion detection due to its simplicity, low power consumption, and effectiveness in detecting body heat emitted by both animals and humans. Specifically, the HC-SR501 PIR module offers a detection range of up to 7 meters [20] and allows for adjustments in sensitivity and trigger delay. In contrast to ultrasonic sensors, which detect any object regardless of thermal characteristics, or microwave radar sensors that are more expensive and susceptible to false positives in open environments, the PIR sensor excels at distinguishing living creatures by sensing infrared radiation. This capability makes it particularly well-suited for monitoring wildlife, where only warm-blooded intrusions, such as leopards and honey badgers, are of interest.

Another key factor in choosing a PIR sensor is its minimal power requirement. Operating at just 5V with very low current draw, the PIR sensor is ideal for battery or solar-powered applications in outdoor environments. Additionally, its digital output simplifies interfacing with the ESP32-CAM, reducing the need for complex signal processing or calibration routines. While camera-based or acoustic motion detection methods were considered, they were ultimately dismissed due to higher computational and power demands, increased cost, and susceptibility to environmental noise. The PIR sensor's balance of reliability, efficiency, and cost-effectiveness made it the most practical solution for real-time animal presence detection in this context.

3.3.3 Image Classification

Machine learning was chosen as the classification method because it provides superior accuracy and adaptability when dealing with complex and variable visual input, such as identifying different animal species in uncontrolled outdoor environments. Traditional rule-based image processing using edge detection, colour thresholding, or template matching is typically fragile and cannot generalise well to different lighting conditions, animal poses, or background textures. In contrast, convolutional neural networks (CNNs) trained on labelled datasets can learn high-level features that enable robust classification of animals like honey badgers and leopards, even with variations in appearance or orientation.

Additionally, machine learning models offer the flexibility to be retrained with new classes or updated datasets without redesigning the underlying algorithm. This scalability is crucial for long-term deployment in dynamic wildlife monitoring systems, where new species or environmental changes may necessitate updates. In this project, TensorFlow was used to develop a compact but effective classification model, deployed on a web server to interpret images sent by the ESP32-CAM.

3.3.4 Communication

A client-server architecture was selected to handle image classification due to its simplicity, modularity, and flexibility in deployment. In this setup, the ESP32-CAM acts as a client, capturing and sending images via HTTP POST to a web server that hosts the classification model. This separation of roles allows each component to focus on its strengths; the ESP32-CAM handles hardware-level sensing and communication, while the server leverages the computational resources needed to run a full TensorFlow-based machine learning model. Using Flask, a lightweight, Python-based framework, simplifies the creation of RESTful endpoints and allows seamless integration with existing AI libraries. This architecture also supports easy testing, debugging, and future upgrades. Because the model runs on the server, updates to the classification algorithm can be made without reprogramming the ESP32-CAM. Moreover, the server can log detections, generate visual dashboards, or even control deterrents remotely if needed. Alternative approaches, such as performing on-device inference with TensorFlow Lite or using MQTT protocols, were considered but were either limited by memory constraints or unnecessarily complex for a system with basic interaction needs. Flask offers a good balance between usability and capability, enabling fast development, accurate classification, and straightforward communication in a distributed sensing application.

3.4 Final Design

3.4.1 System Flowchart and Physical Build

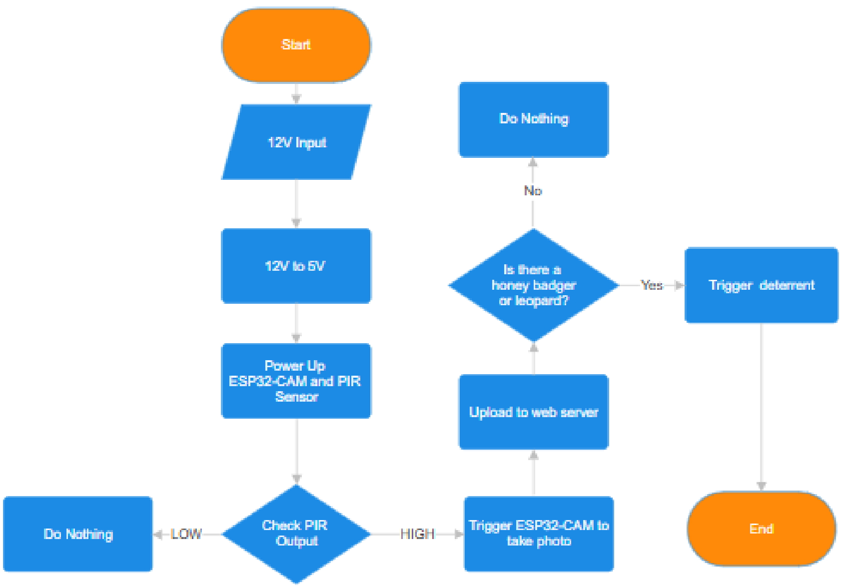


Figure 3.1: Detection subsystem Flowchart

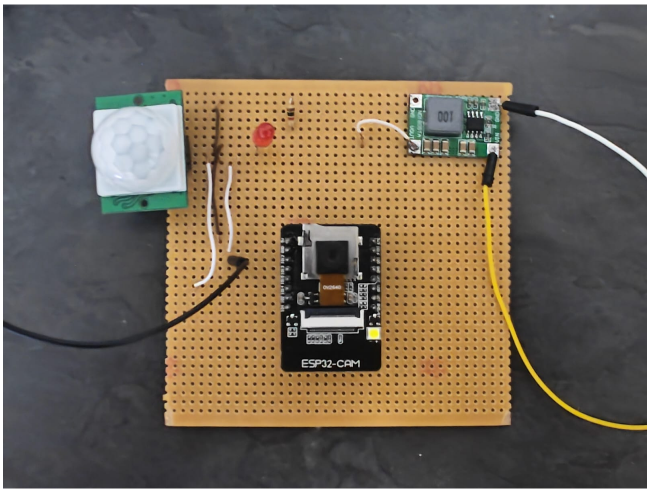


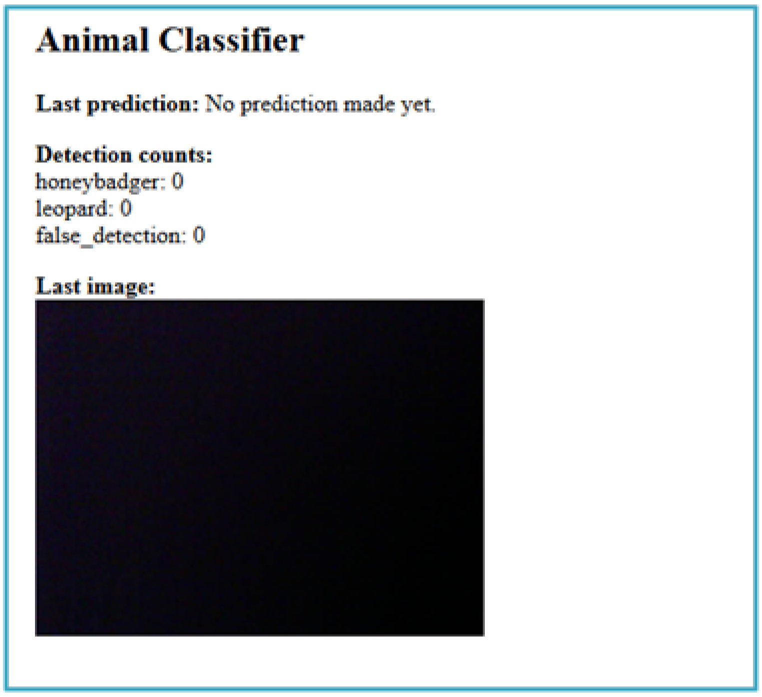
Figure 3.2: Physical build

3.4.2 Web Server Interface

The web server in this system acts as a simple user interface and control point for monitoring animal detections made by the image classification model. Built using Flask, the server runs locally on the ESP32-CAM's backend system (e.g., a Raspberry Pi or PC), and handles three main tasks: receiving images for classification, storing the latest image and prediction result, and displaying a summary of detections on a webpage. When an image is captured by the ESP32-CAM, it is sent as a raw byte stream via an HTTP POST request to a dedicated endpoint. This image is first pre-processed and saved locally for display. The server then uses a machine learning model to analyse the image and determine whether the animal depicted is a honey badger, a leopard, or if it is a false detection. The classification result is stored in memory. It also increments an internal count for that specific category. This real-time status is accessible through the home page of the web server, which is reached via a browser by navigating to the server's IP address. The home page presents a summary showing the most recent prediction, a count of how many times each animal or false detection has occurred and displays the last image that was uploaded and processed. This visualisation allows users to verify the classifier's performance and system activity directly through a graphical interface. Figure 3.3 below shows a snapshot of the webpage produced by this server. It displays the last classification (in this case, none yet), detection counts for each category, and the most recently received image. The layout is minimalistic and intuitive, making it suitable for remote conservation field monitoring applications where simplicity and clarity are essential.

This server-side implementation is supported by the underlying code provided in the appendix section A.3, which contains the logic for three main endpoints: the home endpoint, the classify endpoint, and the last image endpoint. The home endpoint is responsible for rendering the HTML content seen on the webpage. The classify endpoint handles the image data sent from the camera, runs it through the machine learning model, and updates the prediction results. The last image endpoint sends the most recently received image back to the browser for display. Together, these components create a lightweight yet functional system for monitoring potential threats like predators near penguin colonies in real time. This modular structure allows for easy extension. For example, additional classes could be added by retraining the model and updating the class list. Similarly, more advanced detection statistics,

Figure 3.3: Web Server Interface



visualisations, or alerting mechanisms could be integrated in the future without major architectural changes.

3.5 Results and Analysis

3.5.1 ATP Results

Table 3.6: Acceptance Test Procedures and Results

ID	Test Procedure	Success Criteria	Result
ATP-1	Connect ESP32-CAM to a regulated 5V power supply. Flash a basic blink/test sketch. Observe LED and measure current.	ESP32 powers up correctly; red LED blinks and current draw is within safe limits.	**PASS.** ESP32-CAM consumed approximately 200 mA at 5V. The red LED blinked successfully.
ATP-2	Power the HC-SR501 PIR sensor with 5V and GND. Connect OUT pin to GPIO on ESP32-CAM. Monitor Serial output on motion.	Console prints "Motion detected!" when a person moves within $\sim$7 meters.	**PASS.** PIR sensor triggered motion detection at 6.5 meters. Serial output confirmed detection.
ATP-3	Flash code to ESP32-CAM that waits for PIR signal and then captures an image. Move in front of sensor and observe Serial response.	Image capture occurs only when PIR triggers HIGH.	**PASS.** Image capture triggered only after the PIR input went HIGH. Serial showed capture confirmation.
ATP-4	Test OV2640 camera image capture by running capture-only code.	Image captured successfully with camera.	**PASS.** Captured images succesfully captured. JPEG output confirmed.
ATP-5	Send an image to Flask server endpoint `/classify` using ESP32-CAM. Confirm receipt and server reply.	Server returns classification result (e.g., "leopard").	**PASS.** Images were successfully uploaded to the `/classify` endpoint. Server returned classification.
ATP-6	Present known photos or physical representations of each class (leopard, badger, human). Record predictions.	Model correctly classifies $\geq$80% of test images.	**PASS.** The model classified with an accuracy of 96.4% when simulated using a database of images.
ATP-7	Connect GPIO pin to relay/LED. Trigger classification of a known predator. Monitor pin state.	GPIO goes HIGH for at least 3 seconds when a threat is identified.	**PASS.** GPIO output pin went HIGH for 3 seconds upon detecting a leopard or honey badger. Relay activated.
ATP-8	Enable deep sleep mode after inactivity. Measure current draw and verify wakeup on PIR input.	ESP32 enters sleep mode (low current $<$ 1 mA), then wakes up on motion.	**FAIL.** Deep sleep was not implemented as Wi-Fi needs to remain active during operation.
ATP-9	Add up all hardware components used (ESP32-CAM, PIR, relay, power module, etc.). Evaluate cost with reference to local prices.	Total cost $\leq$ R750 per unit.	**PASS.** Total hardware cost estimated at R547 per unit.

3.5.2 Testing Procedure and analysis

Physical Testing

The physical testing procedures were conducted to validate the functionality of the ESP32-CAM hardware, the PIR sensor, and the GPIO-based deterrent trigger. These tests ensured that the system components met operational standards under real-world conditions.

ATP-1: Power and Current Verification: A multimeter was used to confirm the voltage and current requirements of the ESP32-CAM. The board was powered with a regulated 5V source, and current draw was observed to be approximately 200 mA. A basic sketch was uploaded to blink the onboard red LED, which confirmed that the device was active and operating within electrical limits.

ATP-2 and ATP-3: Motion Detection with PIR Sensor: The HC-SR501 PIR sensor was connected to the ESP32-CAM, and its digital output pin was linked to a GPIO input on the board. The sensor was tested by walking a human subject across its field of view. Serial output confirmed that motion was reliably detected at a range of approximately 6.5 meters. This validated the sensor's capability in an open environment similar to where penguin conservation would be deployed.

ATP-7: GPIO Output Verification: Upon successful image classification of a predator (such as a leopard or honey badger), the ESP32-CAM was programmed to trigger a GPIO pin. The output was monitored using a multimeter, which confirmed that the pin went HIGH for 3 seconds after detection. This was further validated by connecting an LED and relay to simulate activation of the deterrent system.

Model Testing

Model testing focused on the ability of the system to accurately capture, classify, and respond to animal presence using machine learning deployed on a web-based server.

ATP-4: Camera Capture Confirmation: When motion was detected and the ESP32-CAM triggered, the image was captured using the OV2640 module. Capture success was monitored by logging messages in the Flask web server.

ATP-5: Server Classification Response: Once an image was uploaded to the Flask web server, the server responded with a prediction label such as 'leopard', 'honey badger', or 'false detection'. These responses were printed to the ESP32-CAM's serial monitor. Receipt of a valid classification string indicated a successful pass for this ATP.

ATP-6: Model Accuracy and Confusion Matrix The image classification model was trained using a labelled dataset and implemented in TensorFlow. During simulation testing, it achieved an overall accuracy of 96.4%. The code for the model can be found on the project git repo in the appendix section A.2. Additional validation was performed using a confusion matrix.

Figure 3.4 shows a 2×2 confusion matrix that demonstrates the model's strong discriminative capability, particularly in minimizing false positives, which is critical in avoiding unnecessary triggering of the deterrent system.

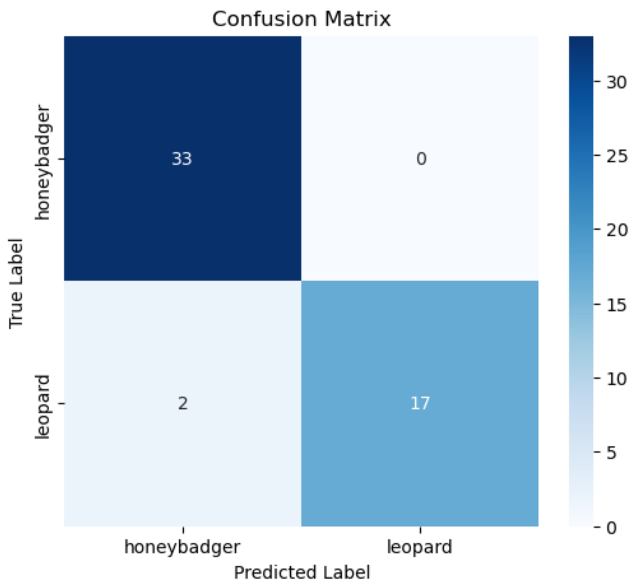


Figure 3.4: Confusion Matrix

3.6 Conclusion

The Predator Detection and Classification subsystem was successfully designed, implemented, and tested to fulfill the core objectives of the automated sprinkler-based deterrent system. The integration of the ESP32-CAM, HC-SR501 PIR sensor, and OV2640 camera module enabled reliable real-time detection of animal motion and effective image capture. Testing confirmed that the system could detect motion up to 6.5 meters, trigger image capture only when motion was present, and transmit the image over Wi-Fi to a Flask-based server running a TensorFlow classification model. The model achieved an accuracy rate of 96.4% during evaluation, confirming its effectiveness in distinguishing between leopards, honey badgers, and non-threatening classes such as humans.

Hardware-level testing also validated the system's response capability, with the GPIO output successfully activating upon detection of a predator and interfacing correctly with the deterrent subsystem. The total cost of the unit remained well under budget constraints, confirming the system's affordability and suitability for deployment in conservation areas. Although the system could not enter deep sleep due to the need for continuous Wi-Fi connectivity, all other functional and performance criteria were met.

This subsystem is a crucial component in the broader effort to protect vulnerable penguin colonies from predators. By combining motion detection, smart classification, and automated deterrent triggering, the system provides a low-cost, low-maintenance solution for real-time wildlife monitoring and response. Its successful deployment supports sustainable conservation practices by reducing predation with minimal human intervention and without disrupting the natural environment.

Chapter 4

Predator Deterrent - NTSMAS030

Different deterrent strateges, together with their advantages and disadvantages have been reviewed in chapter 2. A common cause of failure was identified to be habituation. An innovative approach has been taken in the development of an '**Automated Sprinkler-Based Predator Deterrent System**. 'The 'Automated Sprinkler-Based Predator Deterrent System' has to two main subsystems, namely **Predation Detection** and **Predator Deterrent**. This section focuses on the Predator Deterrent subsystem, providing a rationale for the selected deterrent technique. It also outlines the theoretical framework supporting the subsystem and its alignment with the overall project objectives.

4.1 Subsystem Overview

The proposed deterrent solution is required to meet several critical design constraints to ensure functional effectiveness, safety, compatibility, and acceptability.

Table 4.1: Limitation that the solution must satisfy

Limiation ID	**Description**
LM01	Must be non-harmful to predators.
LM02	Must have low power consumption, ideally solar-powered.
LM03	Easy to install and relocate, with a low footprint and no permanent damage to the installation site.
LM04	Must be water and weather-proof.

These requirements and limitations are systematically addressed through thoughtful component selection and strategic system integration (see section 4.3). During the design development phase, each component is evaluated not only for its ability to meet the defined requirements but also for its performance within the imposed constraints. A comprehensive overview of the resulting subsystem configuration is presented in Figure 4.1.

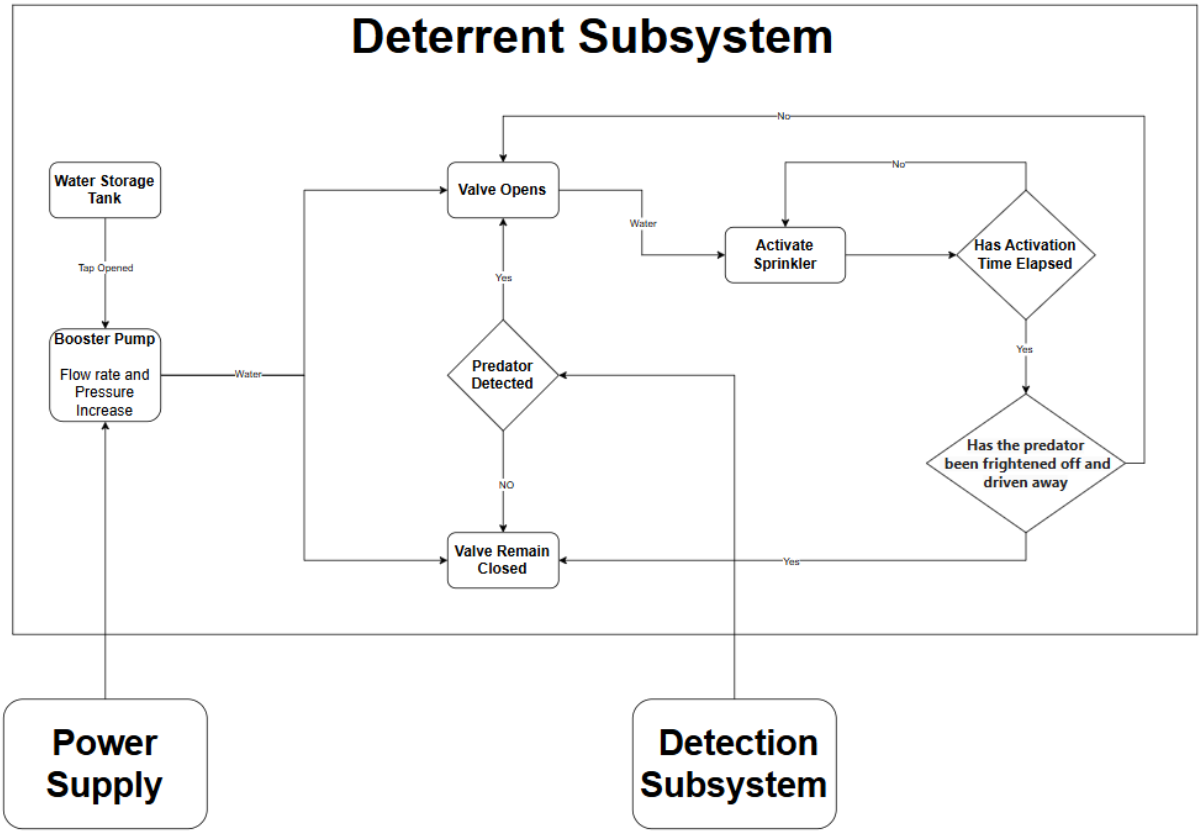


Figure 4.1: Deterrent subsystem overview

4.2 Water as a Deterrent

Penguin colonies are typically found near the ocean, where water is abundant. The system's dependence on this abundant resource ensures that seasonal changes will not impact its optimal performance. The most important requirement for our project is to develop a non-lethal solution that causes minimal to no harm to both the predator (Honey Badgers and Leopards) and prey (Penguins). Penguins have terrestrial and aquatic components [21]. The water-based solution will be friendly to penguins and will not affect daily activities. More importantly, it will not affect mating and reproduction.

Contrary to the penguins being aquatic, honey badgers and leopards are terrestrial animals. The deterrent system seeks to capitalise on this common character. For predators to become habituated to the system, they will have to develop aquatic components. The development of such characteristics requires gradual evolution over a geological time scale.

The 'Research Gap and Critical Thinking Analysis' (section 2.5) demonstrated that isolated techniques are not as effective as systems that combine unique deterrent methods. Therefore, this solution will be integrated with the existing electric fence mechanics at the Boulders Penguin Colony. The primary objective is to keep predators away from the fence that protects the penguins. By keeping them away from the fence, the chances of them becoming familiar with it and subsequently breaking through to attack the penguins will be drastically reduced. This observation should not be construed as an underestimation of the formidable capabilities of these two species. Honey badgers demonstrate exceptional intelligence, adaptability, and hunting proficiency [22]. Similarly, although leopards are not primarily aquatic animals, they possess strong swimming abilities [23].

4.3 Design Development

The main components of the subsystem consist of a **water storage tank, water pump, water control solenoid valve, and a sprinkler**.

4.3.1 Water Storage Tank

The system uses gravity to feed the water into the booster pump. Using the **hydrostatic pressure formula** and a minimum pressure target of **3.1 kPa**, the minimum height of the tank can be determined. The height difference between the water level and exist point will determine the exit velocity of the water. The storage tank has a maximum volume capacity of 20 l.

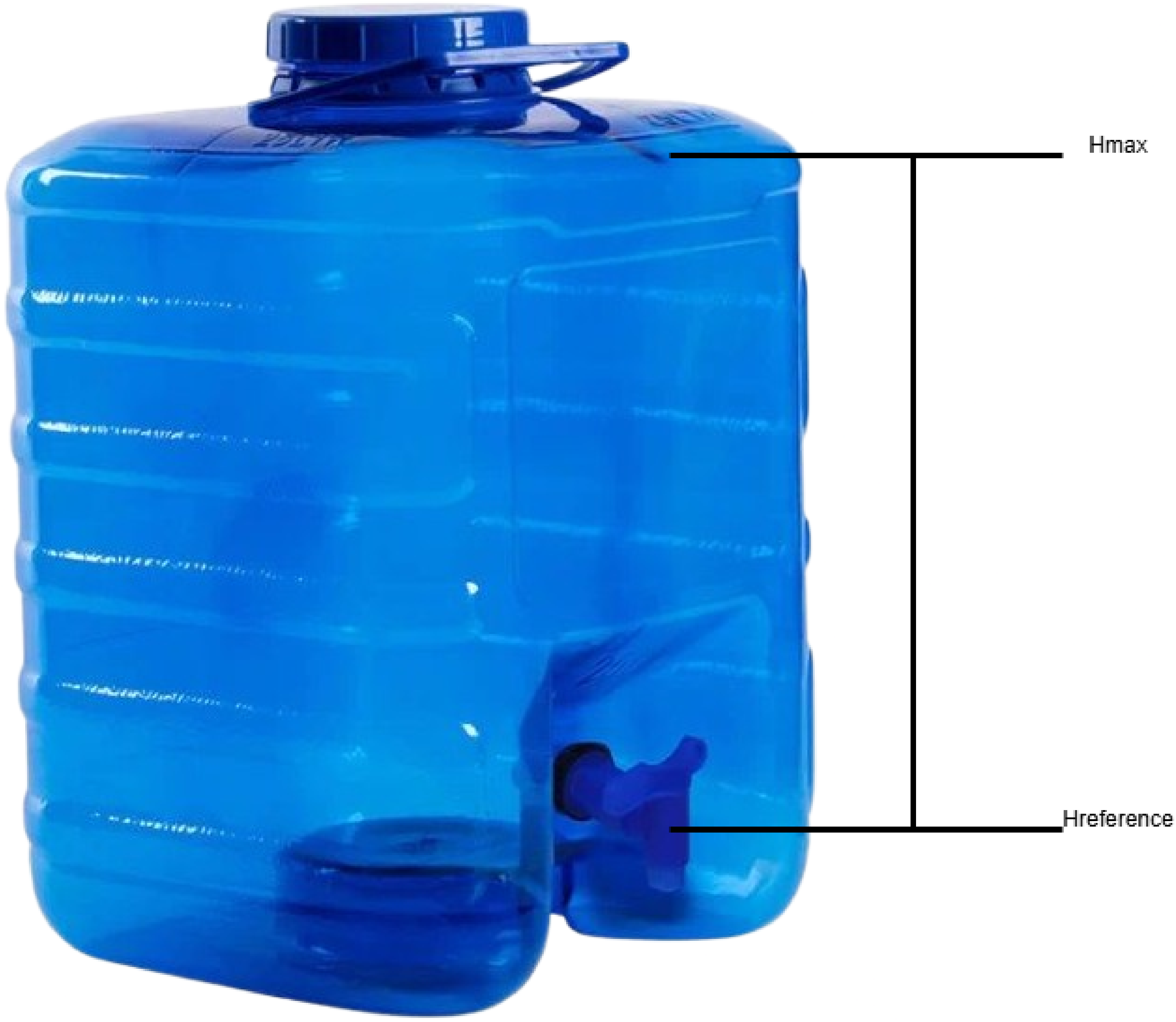


Figure 4.2: Water storage tank with the required minimum height

Solving for h_{min}:

$$\begin{aligned} P &= \rho g h_{min} \\ 3 \cdot 10^3 &= (1000)(9.81) h_{min} \\ h_{min} &= 0.32 \text{ m} \end{aligned} \tag{4.1}$$

where:

- P is the pressure,
- ρ is the water density (1000kg/m^3),
- g is the acceleration due to gravity,
- h is the height difference between the water level and exist point

This is necessary since the pump is not self-priming. Using Bernoulli's principle in fluid dynamics, the exit velocity of the water can be determined as follows:

Calculating v:

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2 \tag{4.2}$$

where:

- v is the water velocity,

The water flowing from a higher point(water level inside the container) to a lower point(exit point) is exposed to the same atmospheric pressure. The rate of flow of the water inside the container is relatively small compared to the velocity at which the water exits the storage tank. The point at which water leaves the tank is used as the reference height. Thus, the equation becomes:

$$\rho g h_1 = \frac{1}{2}\rho v_2^2$$

Since $P_1 = P_2$ (both points are open to the atmosphere)
$v_1 = 0$ m/s (negligible)
$h_2 = 0$ m (reference)

$$v_2^2 = 2gh_1$$

Taking the square root of both sides:

$$v_2 = \sqrt{2gh_1}$$

Substituting $h_{min} = 0.32$ m:

$$\begin{aligned} v &= \sqrt{2gh_{min}} \\ &= \sqrt{2 \cdot 9.981 \cdot 0.32} \\ &= 2.51 \text{ m/s} \end{aligned}$$

After finding the velocity, the water flow rate (Q) can be determined by multiplying the velocity (v) by the cross-sectional area of the tap (A).

Calculating A:

$$\begin{aligned} A &= \pi r^2 \qquad (4.3) \\ &= \pi \cdot (10 \cdot 10^{-3})^2 \\ &= \pi \cdot 10^{-4} \text{ m}^2 \end{aligned}$$

Calculating Q:

$$\begin{aligned} Q &= A \cdot v \qquad (4.4) \\ &= \pi \cdot 10^{-4} \cdot 2.51 \\ &= 7.885 \cdot 10^{-4} \text{ m}^3/s \\ &= 47.31 \;\; l/\text{m} \qquad (4.5) \end{aligned}$$

4.3.2 Water Pump

The water pump in Figure 4.3 can be operated in two different ways. Firstly, it can be submerged in water. Secondly, it can be placed outside the water storage tank. In this project, it is intended to be used as a booster pump; hence, the latter configuration is taken.

Hydrostatically feeding the pump's inlet significantly enhances the efficiency of the water pump by reducing the required lift, lowering power consumption, and minimising overall pumping effort.

- **Reduced Lift Requirement:** The presence of inlet pressure means the pump does not need to expend as much energy lifting water from a lower elevation. The incoming pressure assists in moving the water through the system, leading to less strain on the pump.
- **Lower Power Consumption:** When the pump receives pressured water at the inlet, it requires

less mechanical effort to generate the necessary flow and head. This results in a noticeable decrease in energy usage, improving overall operational efficiency.

- **Minimised Pumping Effort:** Because the water is already under slight pressure, the pump does not need to accelerate the fluid as aggressively. This reduces stress on internal components, enhances longevity, and maintains a more stable and efficient flow rate.

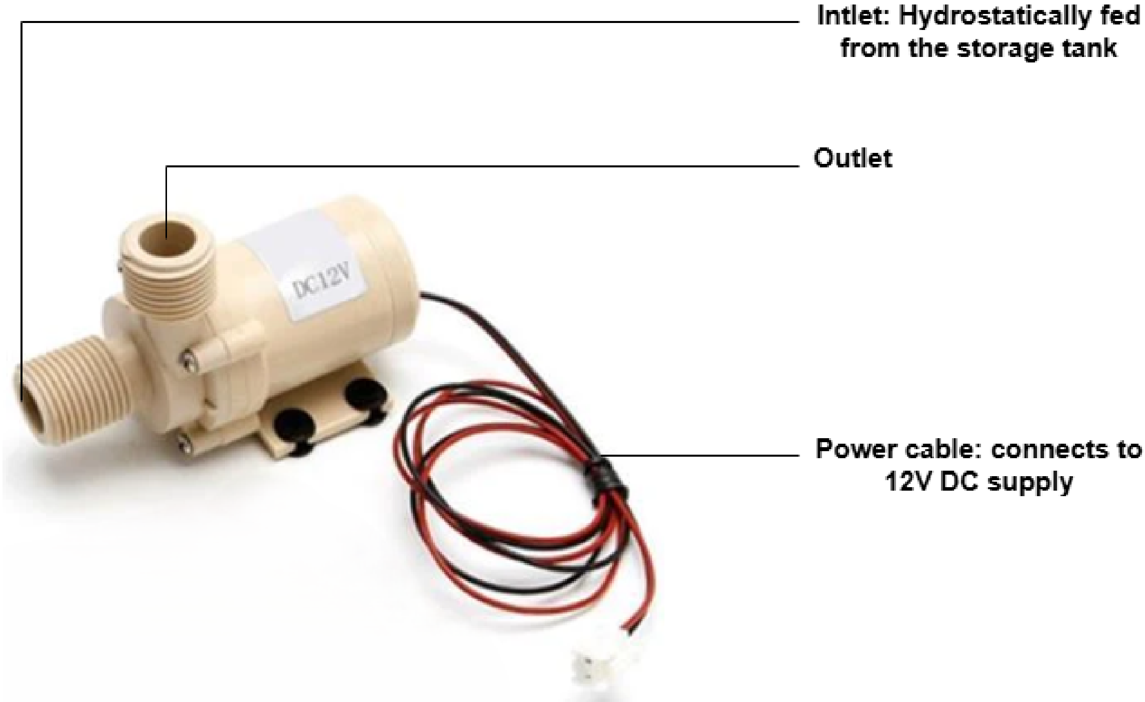


Figure 4.3: DS3502HF Water pump

Pump specification

- Power = 8.4 Watts
- Voltage = 12V DC
- Flow Rate = 480 l/h
- The pump is submersible and can pump water up to a maximum height of 3 m

The pump's ability to operate both submerged and under hydrostatic pressure allows it to endure a variety of environmental and weather conditions. Its low power consumption of 8.4 W, combined with a 12V DC supply, makes it ideal for energy-efficient applications, such as solar-powered systems.

One of the key features of the water pump is its capacity to deliver a flow rate of 480 l/h and achieve a vertical lift of up to 3 m. This performance is critical, as the **Rainjet Black Rotator 360° Micro Head sprinkler** operates effectively within a pressure range of **50 kPa and 200 kPa**, as illustrated in Figure 4.4. Pressures below 50 kPa significantly reduce spray coverage, while pressures exceeding 200 kPa risk damaging the sprinkler's internal components.

4.3.3 Sprinkler

The sprinkler inlet pressure depends on the flow rate of the water pump. A solenoid water valve controls the water flow. Figure 4.4 shows the relationship between pressure and flow rate.

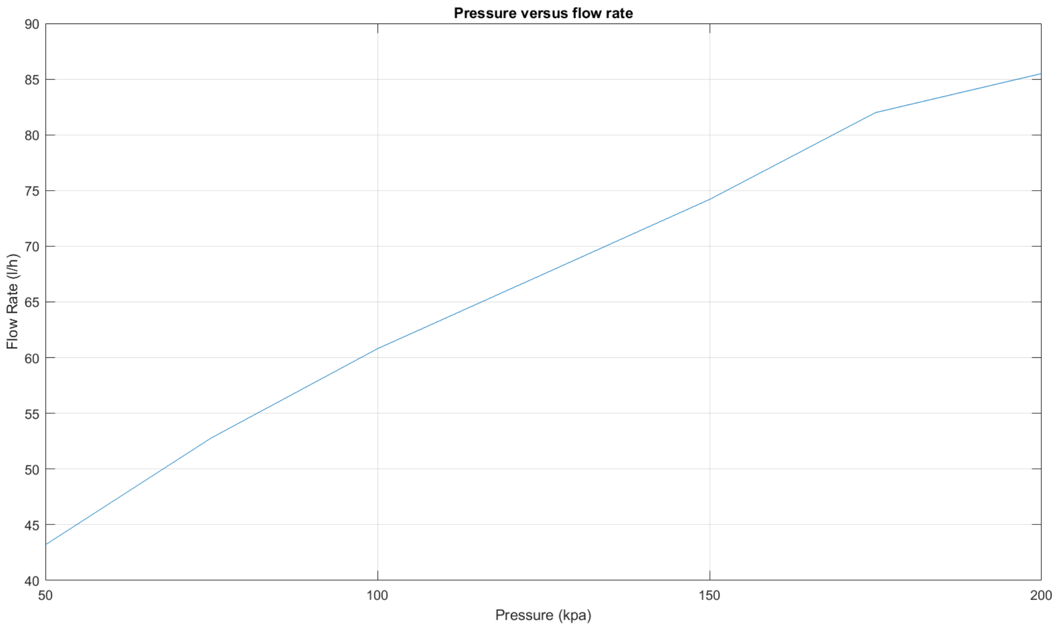


Figure 4.4: Pressure versus flow rate

The sprinkler operation pressure range is close to atmospheric pressure. For our application, it is more optimal to operate the sprinkler at **150 kPa**, which corresponds to a flow rate of **74.2** l**/h**. The sprinkler has an orifice outlet of **1.3 mm** and an inlet diameter of **15 mm** as shown in Figure 4.5. From here, the cross-sectional area can be determined as follows.

Calculating A_{out}**:**

$$\begin{aligned} A_{out} &= \pi r^2 \\ &= \pi(1.3 \cdot 10^{-3})^2 \\ &= 1.69\pi \cdot 10^{-6} \text{ m}^2 \end{aligned} \tag{4.6}$$

The next step is to determine the exit velocity (v_{outlet} at the sprinkler).

Calculating v_{outlet}**:**

$$Q = A_s \cdot v_{outlet} \tag{4.7}$$
$$74.2 \cdot 2.78 \cdot 10^{-7} = 1.69\pi \cdot 10^{-6} \cdot v_{outlet}$$
$$v_{outlet} = 3.89 \text{ m/s}$$

The water at the outlet is open to the atmospheric pressure. Therefore P_{out} = **101.325 kpa**.

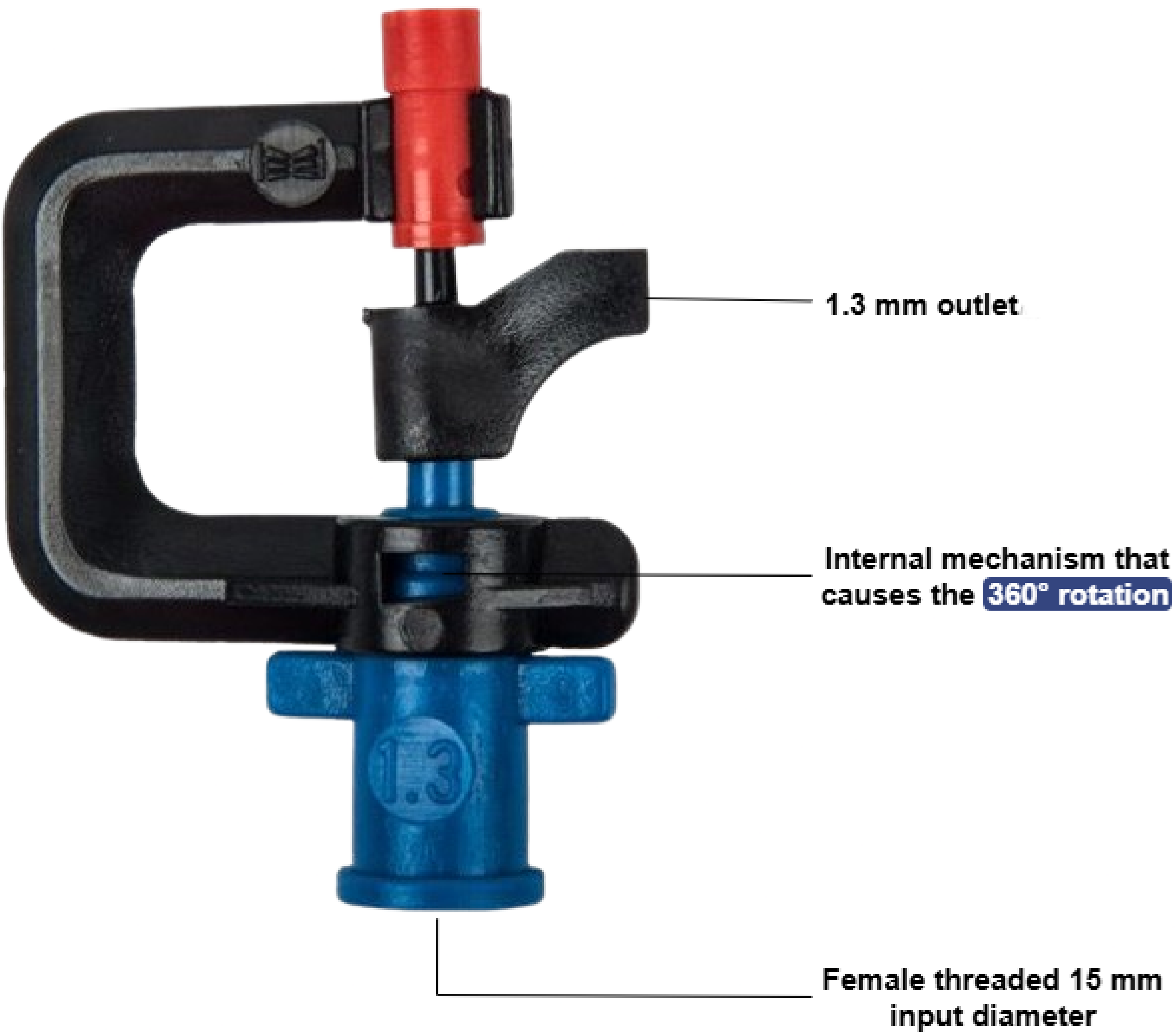


Figure 4.5: Rainjet black rotator 360° micro head spinkler

Spray Radius
The spray radius of a sprinkler depends on the outlet velocity and angle at which the water exits. Using **projectile motion principles**, the radial distance can be calculated as the horizontal range of the water stream. The range is determined by the equation:

Calculating range R:

$$
\begin{aligned}
R &= \frac{v_{outlet}^2 \cdot sin(2\theta)}{g} \\
&= \frac{3.89 \cdot sin(70)}{9.81} \\
&= 1.45 \text{ m}
\end{aligned}
\tag{4.8}
$$

This formula approximates the parabolic trajectory of water droplets, estimating the maximum radial distance reached before falling. However, real-world influences such as air resistance and nozzle design can introduce deviations from the theoretical range, potentially reducing the effective spray radius.

Pressure Maintenance

The inlet pressure is maintained at **150kpa** to maintain a constant rate of **74.2** $\boldsymbol{l}$**/h**. The water pump feeds the sprinkler inlet (480l/h). The inlet water velocity(v_{inlet}) can be determined as follows:

Calculating A_{in}**:**

$$
\begin{aligned}
A_{in} &= \pi r^2 \\
&= \pi(\frac{1}{2} \cdot 15 \cdot 10^{-3})^2 \\
&= 5.625\pi \cdot 10^{-5} \text{ m}^2
\end{aligned}
\tag{4.9}
$$

Calculating v_{inlet}**:**

$$
\begin{aligned}
Q &= A_s \cdot v_{inlet} \\
\frac{800}{3.6 \cdot 10^6} &= 5.625\pi \cdot 10^{-5} \cdot v_{intlet} \\
v_{inlet} &= 1.2575 \text{ m/s}
\end{aligned}
\tag{4.10}
$$

There is a significant change in flow rate (from 480 l/h to 74.2 l/h and pressure from (150kPa to 101.325kPa). These changes necessitate the introduction of a water control valve.

4.3.4 Water Control Solenoid Valve

The solenoid valve serves a critical function within the system. As a normally closed valve, it prevents water flow to the sprinkler in the absence of a detected threat. Upon predator detection, a 12V DC signal is applied to energize the valve, triggering it to open and permit water flow to the sprinkler. The valve remains energized for a preset activation period of 60 seconds, during which more than 1 l of water is dispensed. Key specifications of the solenoid valve are provided below.

- Actuating voltage: 12V DC (but it worked down to 6V)
- Working Pressure: Inlet Valve: 0.02 MPa - 0.8 MPa
- Response time (open): <0.15 sec
- Response time (close): <0.3 sec
- Actuating life : >50 million cycles

The chosen solenoid valve is well-suited for this project due to its ability to handle high-pressure conditions, making it compatible with the system's operating demands. Its wide pressure range ensures safe and efficient operation even under varying pressure conditions. Additionally, the valve's broad temperature tolerance directly addresses the project's environmental constraint, allowing it to perform reliably in varying climates or system heat levels. Its fast response time ensures precise water flow control, which is critical for the timing and efficiency of the overall setup. The valve's low power consumption supports energy efficiency goals and is ideal for integrating low-voltage solar or battery-powered systems. Its lightweight design contributes to the system's overall mobility and ease of installation, while the high number of actuation cycles guarantees long-term durability and minimal maintenance. Collectively, these features make the solenoid valve a robust, efficient, and reliable choice for this project.

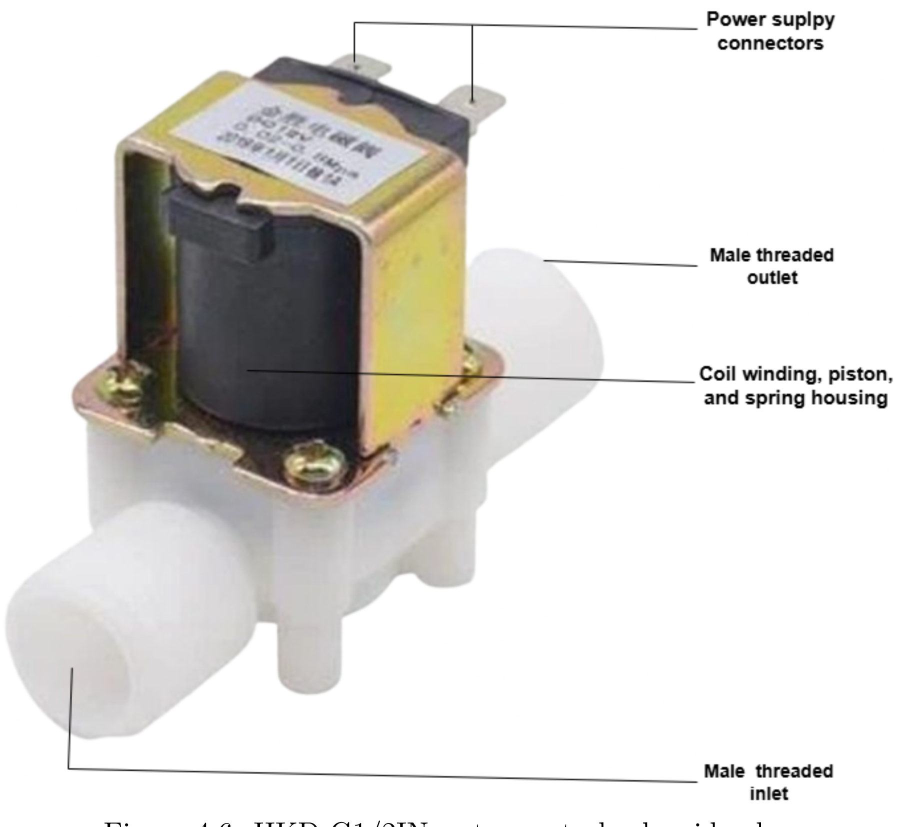


Figure 4.6: HKD G1/2IN water control solenoid valve

4.3.5 HKD Delay Timer

To automate the system's response upon detecting a predator, an HKD Trigger Delay Timer (0.1s–999m) shown in Figure 4.6 is integrated to control the operation of the solenoid valve and the water pump. The timer is configured in Mode P1.1, which enables a triggered delay-off function. This setup ensures that once the sensing system detects a predator, a signal is sent to the timer's trigger input pin.

Upon receiving the trigger, the timer immediately activates the relay output, sending power to the solenoid valve, which opens and allows water to flow to the sprinkler. The timer is pre-set to maintain this output for 60 seconds, after which it automatically deactivates the relay, cutting off the power supply to the solenoid valve and causing it to close.

This design ensures the system responds only when needed, conserves water and power, and minimises the need for manual intervention. Additionally, the timer's support for a wide voltage range, low power consumption, and programmable timing make it highly suitable for integration with renewable or battery-based systems in remote environments.

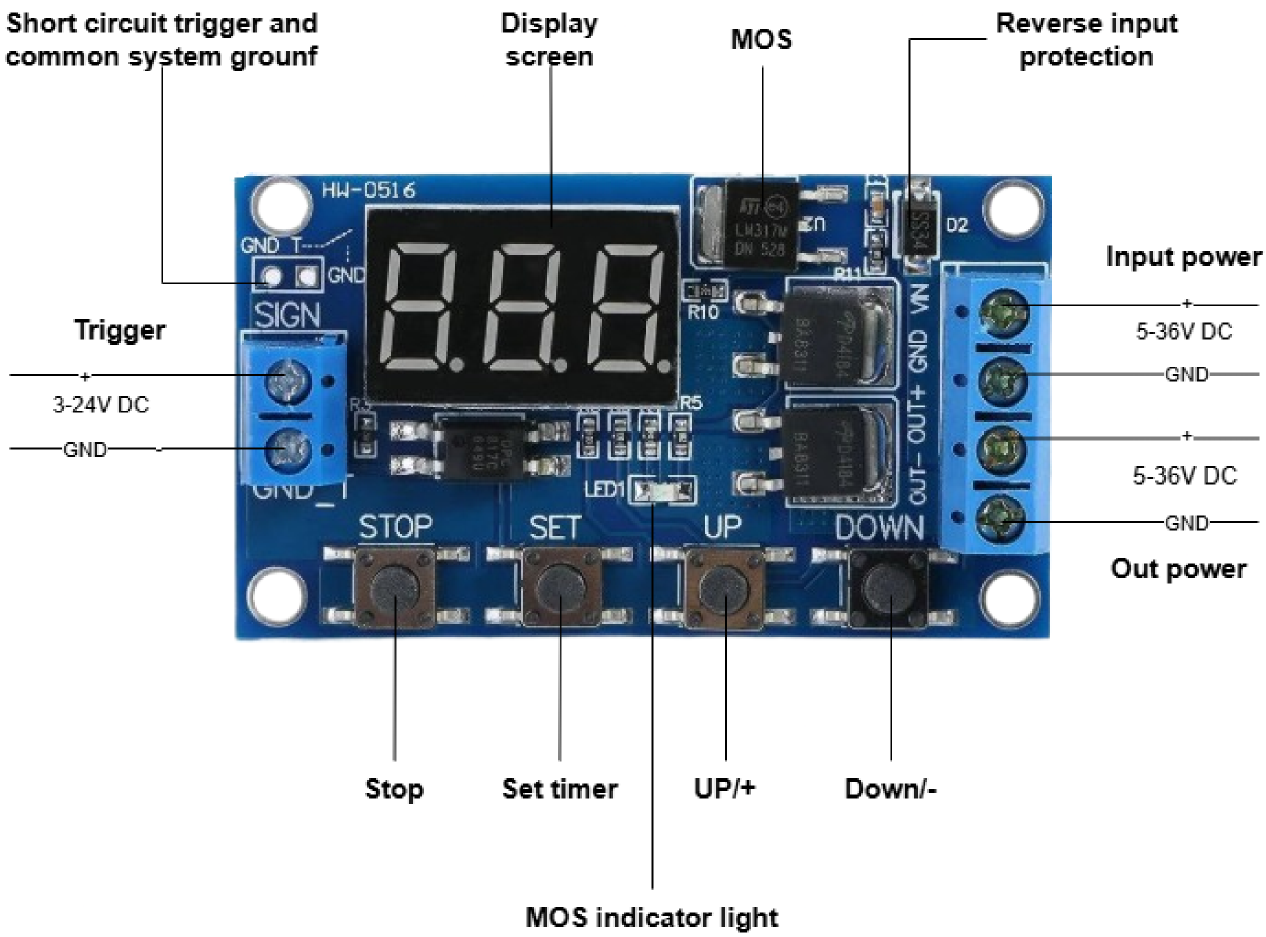


Figure 4.7: HKD delay timer

4.4 System Performance Evaluation

Initial testing revealed a reduced spray radius, primarily due to leakages along the pipeline, which led to unintended pressure losses. This issue was mitigated by reinforcing the sealing integrity at joint connections using sealing tape, significantly improving system efficiency. Following this adjustment, the subsystem demonstrated reliable performance, activating almost instantaneously when triggered and maintaining stable operation throughout testing.

The measured peak current draw of 0.7 A reflects efficient power usage. Although the observed spray radius was slightly less than the theoretical value, this discrepancy can be attributed to multiple non-ideal factors, including internal pipe resistance, minor flow restrictions at fittings, and aerodynamic drag at the sprinkler outlet. Overall, the subsystem meets its functional requirements, delivering consistent operation under practical conditions.

Chapter 5

Conclusions and Recommendations

The purpose of this project was to design and develop an automated, non-lethal predator deterrent system to protect endangered African penguins at the Boulders Penguin Colony from terrestrial predators such as honey badgers and leopards. By addressing the limitations of existing deterrent methods, particularly habituation and environmental constraints the project aimed to create a cost-effective, low-power, and sustainable solution that minimizes human intervention while maximizing ecological compatibility.

This report began with an introduction to the critical challenges facing African penguins in Chapter 1, emphasizing the urgent need for innovative conservation strategies. The background and motivation highlighted the devastating impact of predation on penguin populations and the inadequacy of traditional deterrent systems. The objectives outlined the project's focus on autonomy, non-lethality, and adaptability to harsh coastal conditions.

The literature review in Chapter 2 evaluated existing predator deterrent techniques, including auditory, visual, and physical barriers, as well as guard animals. It identified key research gaps, such as the lack of solutions tailored to non-traditional predators like honey badgers and leopards, and the need for multi-sensory, adaptive systems to combat habituation. This analysis informed the project's hybrid approach, combining motion detection, image classification, and water-based deterrence.

The bulk of the work for this project followed in Chapters 3 and 4, which detail the design and implementation of the two core subsystems: the predator deterrent and the predator detection systems.Chapter 3 presented the detection subsystem, which integrated a PIR sensor, ESP32-CAM, and machine learning to classify threats and trigger the deterrent autonomously with a 96.4% classification accuracy. Chapter 4 explored the water-based deterrent subsystem, leveraging hydrostatic principles to create a hostile yet harmless environment for predators.

Finally, the current section, Chapter 5 summarized the project's achievements and reflected on its broader implications for wildlife conservation. The system's modular design and low-cost components make it scalable for other species and habitats, while its non-lethal approach aligns with ethical wildlife management practices.

In summary, the project achieved its goals by designing and demonstrating a functional prototype that addresses the specific challenges of penguin conservation. The automated sprinkler-based deterrent system offers a sustainable, adaptable, and humane solution to reduce predation, contributing to the long-term survival of African penguins. Future work could explore enhancements for energy savings, expanded predator classification models, and integration with broader conservation networks.

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Appendix A

BOM and individual Appendices

A.1 BOM

Req ID	Supplier	Item Description	Unit Price	Quantity	Total Price
REQ001302_1	DIY Electronics (Local)	ESP32-CAM: WiFi + Bluetooth Camera Development Board	182	1	182
REQ001302_2	Pishop (Local)	ESP32-CAM MB Micro-USB Programmer	39.08	1	39.08
REQ001302_3	DIY Electronics (Local)	PIR Sensor Detector Module	20.8	2	41.6
REQ001302_4	MicroRobotics (Local)	DC-DC Buck Voltage Regulator, Vin 6–18V Vout 5V 4.5A	78.2	1	78.2
REQ001302_5	DIY Electronics (Local)	Solderless Breadboard 400TP	15	1	15
REQ001302_6	DIY Electronics (Local)	Breadboard Jumpers	20.8	1	20.8
REQ001302_7	DIY Electronics (Local)	OLED Display Module White – 0.91-Inch 128x32 4pin For Arduino	55.2	1	55.2
REQ001441_1	Communica (Local)	Veroboard - EXCU21-300	92	1	92
REQ001441_2	Communica (Local)	HKD RIBBON JUMPER 40W M/F 15CM	23	1	23
Sub Total					**546.88**
REQ001278_1	Communica (Local)	HKD G1/2IN WATER FLOW SOLENOID	83	1	83
REQ001278_2	Takealot(local)	Brushless DC 12 Volt Submersible 5m Pump 800l/h	550	1	550
REQ001278_3	Takealot(local)	Rainjet Black Rotator 360Deg Micro Head - 1.3mm	141	1	141
REQ001278_4	Communica (Local)	HKD TRIGGE DELAY TIMER 0.1S-999M	44	1	44
Free	UCT Gardens and Nursery	Water Storage tank	60	1	60
Free	UCT Gardens and Nursery	Coupling fittings	15	4	60
Sub Total					**938**
Total					**1484.88**

Figure A.1: Bill of material

A.2 Github Repository link

https://github.com/nsitwala01/EEE4113F_Project

A.3 Web Server Code

The following code implements the Flask server that handles image classification and serves results to the web interface:

```
from flask import Flask, request, send_file
import numpy as np
import tensorflow as tf
import cv2
import os

app = Flask(__name__)
model = tf.keras.models.load_model("animals.keras")  # 2-class model

CONFIDENCE_THRESHOLD = 0.9
CLASS_NAMES = ['honeybadger', 'leopard']

last_prediction = "No prediction made yet."
last_confidence = 0.0
detection_counts = {'honeybadger': 0, 'leopard': 0, 'false detection': 0}
last_image_path = "last_image.jpg"

def preprocess_and_save(img_bytes):
    with open(last_image_path, 'wb') as f:
        f.write(img_bytes)
    nparr = np.frombuffer(img_bytes, np.uint8)
    img = cv2.imdecode(nparr, cv2.IMREAD_COLOR)
    img = cv2.resize(img, (240, 240))
    img = img.astype(np.float32) / 255.0
    return img

def predict_image(image):
    img_array = np.expand_dims(image, axis=0)
    pred_probs = model.predict(img_array, verbose=0)[0]
    max_prob = np.max(pred_probs)
    predicted_class = np.argmax(pred_probs)
    if max_prob < CONFIDENCE_THRESHOLD:
        return "false_detection", max_prob
    return CLASS_NAMES[predicted_class], max_prob

@app.route('/')
def home():
    count_display = "<br>".join([f"{cls}: {count}" for cls, count in detection_counts.items
```

```
    ()])
    image_html = f'<img src="/last_image" width="300">' if os.path.exists(last_image_path) else "No image received yet."
    return f"""
    <h2>Animal Classifier</h2>
    <p><strong>Last prediction:</strong> {last_prediction}</p>
    <p><strong>Detection counts:</strong><br>{count_display}</p>
    <p><strong>Last image:</strong><br>{image_html}</p>
    """

@app.route('/classify', methods=['POST'])
def classify():
    global last_prediction, last_confidence, detection_counts
    if not request.data:
        return "No image data received", 400
    try:
        img = preprocess_and_save(request.data)
        label, confidence = predict_image(img)
        last_prediction = label
        last_confidence = confidence
        detection_counts[label] += 1
        return f"{label} (confidence: {confidence:.2f})"
    except Exception as e:
        return f"Error processing image: {str(e)}", 500

@app.route('/last_image')
def last_image():
    if os.path.exists(last_image_path):
        return send_file(last_image_path, mimetype='image/jpeg')
    return "No image available", 404

if __name__ == '__main__':
    app.run(host='0.0.0.0', port=5000, debug=False)
```

Listing A.1: Flask-based classification server code

Appendix B

GA Tables

B.1 GA Table - STWNAN001

	Graduate Attribute	Evidence from Report
GA 3	Engineering Design	Section 3.2 demonstrates a clear design process starting with user and functional requirements, design choice justification is done in Section 3.3, and a complete implementation described in Section 3.4.
GA 7	Sustainability and Impact of Engineering Activity	Sustainability is addressed through the use of low-cost, low-power components (ESP32-CAM, HC-SR501) to enable deployment in remote conservation areas Sections 3.3.2 and 3.5.2). The system is designed to be non-lethal following the user requirements in Section 3.2.1 and minimally invasive to the environment.
GA 8	Individual, Team and Multidisciplinary Working	Evidenced from the GitHub Repository section A.2 and the MS Teams Group.
GA 10	Engineering Professionalism	All project deliverables were submitted on time, demonstrating strong time management and accountability. Professionalism is shown in the rigorous testing and verification of system components using formal Acceptance Test Procedures (ATP 1–9 in Section 3.5.1). Ethical considerations are met by designing a non-harmful detection and deterrent mechanism.

Table B.1: Graduate Attribute Mapping with Evidence from the Report

B.2 GA Table - NTSMAS030

	Graduate Attribute	Evidence from Report
GA 3	Engineering Design	section 4.1 demonstrates a structured engineering design process incorporating problem definition and requirements analysis. Components were carefully selected and integrated to meet performance, safety, and environmental constraints (throughout chapter 3). The final solution balances functionality, efficiency, and practical feasibility.
GA 7	Sustainability and Impact of Engineering Activity	The system promotes sustainable practices by utilising low-power components and enabling solar-based operation, reducing dependency on grid electricity (see subsection 4.3.2, subsection 4.3.4 and subsection 4.3.5). It minimises water waste through controlled activation (subsection 4.3.4), and its non-lethal deterrent approach ensures minimal environmental disruption while addressing human-wildlife conflict (section 4.2).
GA 8	Individual, Team and Multidisciplinary Working	Effective collaboration is evidenced through coordinated efforts documented in the GitHub Repository (section A.2) and consistent communication via the MS Teams Group..
GA 10	Engineering Professionalism	All project deliverables were submitted on time, demonstrating strong time management and accountability. The system was designed with adherence to relevant safety standards, ensuring responsible and professional engineering practice throughout the project (see section 4.4).

Table B.2: Graduate Attribute Mapping with Evidence from the Report