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Robotic Monitoring of Bird Presence in Pantanos de Villa Wildlife Refuge

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ABSTRACT

Wetlands are among the most productive and ecologically important ecosystems on Earth, yet they are increasingly threatened by urban expansion, pollution, and habitat degradation, particularly at Pantanos de Villa Wildlife Refuge (PVWR), a coastal Ramsar wetland surrounded by the rapidly growing city of Lima, Peru. Birds are widely recognized as effective bioindicators of wetland conditions because their presence, abundance, and distribution respond rapidly to changes in habitat quality, water levels, and food availability. However, conventional bird monitoring relies on manual observation, which is costly, temporally limited, and can disturb wildlife.

This study investigates whether a low-cost autonomous robotic platform can address these limitations by recording bird presence with minimal disruption. A robotic monitoring system was constructed from low-cost recycled materials and 3D-printed connectors, using an Arduino Mega, an HC-SR04 ultrasonic sensor, and an ESP32-CAM to autonomously detect movement and capture images without human supervision. The system was evaluated through controlled testing, a field deployment at PVWR, and a benchtop characterization of the ultrasonic sensor.

During controlled testing, the system consistently logged detection events. The ultrasonic sensor achieved 100% detection reliability within its main lobe, decreasing to 70–90% at the fringe and 10–40% within the side lobes. The camera successfully captured an image for every valid sensor detection. Although no confirmed bird detections were recorded during the single field trial, despite birds being present nearby, the results demonstrate the technical feasibility of a low-cost, non-invasive autonomous bird-detection platform. However, this work represents a proof of concept rather than a validated environmental-monitoring tool, and further field validation alongside independent environmental measurements is needed to establish bird presence as an indicator of wetland condition.

INTRODUCTION

Research question: How can a robotic monitoring system be used to autonomously detect and record bird presence in the Pantanos de Villa Wildlife Refuge?

Wetlands serve an extremely important function as one of the most productive ecosystems on the planet. They provide critical ecosystem services to both wildlife and humans including helping to protect and improve water quality; providing important habitats for many animals; holding excess water from floods; and keeping surface water flowing during dry weather [1]. They are extremely sensitive to damage from human activities, such as pollution, and are very much affected by climate change [2, 3]. In urban coastal areas like Pantanos de Villa Wildlife Refuge, rapid growth of urban developments adjacent to the Refuge and the presence of untreated waste water runoff pose serious threats to both the quality of the water and the abundance of migratory birds that depend on the Refuge for habitat [4].

Animal species are effective bioindicators of environmental conditions [5, 6]. Particularly, waterbirds populations may act as sentinel species for natural and man-made toxicological problems in the environment as they respond quickly to changes in habitat quality, water levels and food availability [7, 13]. For this reason, bird observation has been used as a method to evaluate ecological conditions in protected areas.

However, current traditional ecological monitoring methods commonly employ researcher manual observations. This method is very costly in time [8], extremely restricted in its sample frequency and temporal resolution [9] and dependent on an actual field human presence, which can have impacts on animal behaviors and cause subjective observations [10]. Automation of data acquisition using technological tools can contribute to record information with more precision in time and at greater frequency.

Specifically, Pantanos de Villa Wildlife Refuge (PWVR) is a natural protected area located in the coastal region of Lima, Peru. The wetland, the most of last coastal ones in the region, harbors a diversity of over 200 bird species (both resident and migrant) that make use of it as an essential stopover area on their migratory routes across the Americas. In addition to birds, PWVR supports an important biodiversity, offering also several environmental services like water filtering, flood control, and home for numerous flora and fauna species. Nevertheless, the proximity to a large city (Lima) has caused several pressures such as pollutant spills and discharges that negatively affected the overall biodiversity and environmental services of the ecosystem [3].

To address these challenges, this study utilizes an engineering-driven fieldwork approach. We designed, fabricated, and deployed a low-cost, automated floating platform constructed from sustainable recycled materials. Operating via an integrated microcontroller architecture (Arduino Mega and ESP32-CAM), the robot employs ultrasound for detection and triggers high-resolution cameras and an inertial measurement unit for proximity-based non-invasive identification, tracking, and mapping of local bird species.

The hypothesis of the proposed study is that an automated floating robotic system can autonomously detect the presence of nearby birds and photographically record them with minimal environmental disruption, providing an initial technical foundation toward the eventual development of a comprehensive dataset for wetlands monitoring.

LITERATURE REVIEW

Wetlands are dynamic ecosystems that require continuous monitoring to understand changes in biodiversity, water conditions, and ecosystem health. Environmental monitoring of wetlands commonly includes measuring physical and biological indicators such as water quality, vegetation composition, and species diversity. These indicators help researchers evaluate the ecological status of wetland systems and detect early signs of environmental degradation. Because wetlands are often exposed to pollution, urban expansion, and climate-related changes, long-term monitoring programs are essential for effective conservation and management [4].

These monitoring schemes can fail to reveal quickly occurring changes in the wetlands ecosystem because it is difficult to monitor on a continual basis, or more broadly, from point to point in space and time. Monitoring programs typically depend on researchers or conservation staff conducting periodic surveys, which means that important ecological changes occurring between observations may go undetected. As a result, scientists have increasingly explored alternative monitoring approaches that integrate biological indicators and automated technologies to improve the efficiency and consistency of environmental data collection.

Bio-indicators are specific living organisms whose observable biological attributes reflect an organism's or community's ecological conditions and can be measured, assessed, and analyzed to provide an indication of environmental quality. Bird species are one of the group of organisms commonly considered as bioindicators of wetland environment conditions [5]. The choice of particular organisms for a given purpose depends on the type of bio-indicator and its relationship with ecosystem conditions (species presence and abundance or some other measurable characteristics such as body condition) in particular, environmental factors that indicate the response of the system (such as food or shelter availability) [7].

Research shows that the value of waterbirds as bioindicators can be effectively harnessed through their observable spatial and temporal distribution. Because avian species select habitats based on immediate resource availability, shifts in occupancy, population density, and visit frequency serve as direct, macroscopic characteristics for underlying ecosystem health and habitat stability [7, 15]. Studies have demonstrated that changes in bird abundance and diversity can indicate alterations in habitat quality or pollution levels, making bird monitoring a tool for evaluating wetland ecosystem health [6, 7, 14].

Recent technological advancements in environmental monitoring technologies has made it possible to do so using novel approaches. Automated monitoring systems, such as automated cameras and acoustic sensors, are widely being deployed to collect information about the environment and wildlife that does not necessarily require the attendance of researchers on-site [8, 9, 16, 17]. This can also facilitate collection over wider geographic ranges and for prolonged time periods than might be feasible by manual approaches.

Automated image and sensor technology has shown significant promise for wildlife population surveys. In addition to other animal and ecological metrics, automated visual and acoustic monitoring techniques may be particularly useful for monitoring birds. Advances in artificial intelligence and computer vision have further enhanced these technologies by enabling automated identification of species. Studies have shown that machine learning models can accurately detect and classify bird species from camera trap images, reducing the time and labor required for manual data analysis [18, 19].

Robotic sensor-based monitoring systems also offer the potential to collect environmental data in real time. These systems can operate continuously in remote or sensitive environments, providing consistent data that may improve understanding of ecosystem dynamics. By combining biological observations with automated technologies, researchers can develop more efficient methods for monitoring biodiversity and environmental change.

Despite the widespread implementation of automated technologies into ecological research domains, most current monitoring systems remain prohibitively expensive or require extensive technical infrastructure that may not be available at smaller scale conservation projects or protected areas. Environmental monitoring of many wetlands – especially in developing regions – continues to rely largely on manually performed observational efforts and periodic surveys.

This restrictiveness impedes frequent data gathering and detection of swift environmental alterations. Yet during the last ten years automated monitoring systems have transitioned away from experimental prototyped devices towards becoming critical elements in conservational methodologies. For example, unmanned aerial vehicle (UAV) or drone technology has been broadly adopted as a means of carrying out automated aerial surveys of waterfowl population counts in expansive open wetland zones. With access to high-res imagery and automated computer-vision algorithms UAV platforms enable researchers to survey both nesting pair abundances and landscape-scale shifts in habitat availability within vast stretches of land otherwise impossible to traverse by foot. Unfortunately however, limitations including brief battery life periods, high cost-of-acquisition, and the necessity of having an appropriately licensed operator onsite greatly constrain opportunities for undertaking continuous, long-term monitoring activities [22, 23].

Terrestrial camera traps using PIR sensors to trigger photographs have been widely used as standard equipment for studying the presence of wildlife along game trails and along shore lines. These stationary setups can be used very efficiently to capture long-term non-intrusive data but are inherently static.

As such, deploying them in dynamic wetlands that experience shifting water-levels puts them at risk of being flooded [20, 21].

Although there have been many studies exploring the usage of various automated monitoring technologies in wildlife research, few have investigated how low cost robotic systems can be developed specifically for wetland monitoring.

Providing affordable technological solutions will allow conservation organizations to better gather ecological data for more effective environmental management [22].

The development of these types of engineered solutions has been attempted using more specialized forms of robotic hardware ranging from autonomous surface vessels (ASVs), through to amphibious rovers capable of operating within aquatic spaces while autonomously collecting metrics regarding both water quality and proximity based photographs of local fauna. Despite the significant potential afforded by these approaches, most devices remain sophisticated and expensive instruments requiring costly GPS telemetric capabilities, intricate lidar navigation processes, and highly specialized manufacturing techniques [23].

This study explores the potential for implementing a financially accessible monitoring platform capable of tracking bird presence that could be used to track environmental conditions within the wetland ecosystem surrounding Pantanos de Villa Wildlife Refuge.

SITE REVIEW

Pantanos de Villa Wildlife Refuge (PVWR) is a coastal wetland located within the district of Chorrillos, Lima, Peru. It contains diverse ecosystems such as lagoons, marshes, reeds beds and coastal vegetation, representing one of the few remaining natural wetlands in this highly urbanized region of the country's capital city.

The PVWR has been declared a protected natural area based on its importance to the region's ecology, and recognized internationally as a “Ramsar wetland” of global significance for the conservation of biodiversity [24].

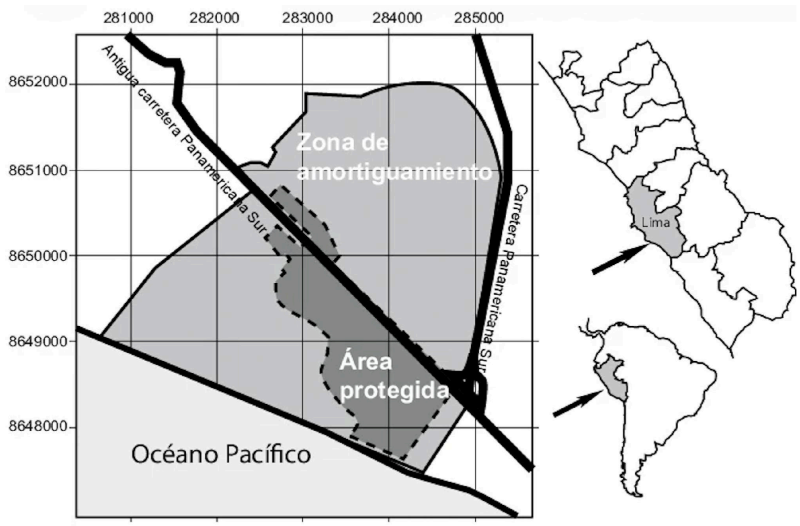

Figure 1: Map of Pantanos de Villa Wildlife Refuge, Chorrillos, Lima, Peru. Source: ResearchGate [30].

Figure 1 shows the distribution of the Pantanos de Villa Wildlife Refuge, located in the southern region of Lima, the capital of Peru. The darker shaded area indicates the officially designated protected zone ("Área protegida", "Protected Zone"), where conservation measures are strictly enforced to maintain the ecological integrity of the wetland. This core area is surrounded by the lighter shaded area called the buffer zone ("Zona de amortiguamiento"), which is intended to reduce the impact of urban activities on the ecosystem. The sanctuary is situated in a metropolitan area and this zoning emphasizes the conservation priorities and the pressures of urban expansion.

The wetland system receives its input from groundwater, coastal influences and irrigation channels feeding wetland and lagoons. This results in a mixture of habitats that harbour a wide diversity of plant and animal species. The refuge's vegetation consists of totora reeds and other species, which provide vital habitat for wildlife and contribute to the ecological functioning of the ecosystem [30].

The Pantanos de Villa Wildlife Refuge is especially famous for its great diversity of birds. The wetland is home to over 200 species of birds, including resident species, migratory birds and occasional visitors [25, 26]. These birds originate from different regions like North America, the Andes and other areas of South America making the wetland an important stopover site for migratory routes.

Studies of bird populations in the wetland have identified both resident and migratory species that use the ecosystem for feeding, nesting and resting during migration. Research conducted in the area has registered several species from multiple bird families and ecological groups [27], pointing out the ecological complexity of the site.

The Pantanos de Villa Wildlife Refuge is a protected area, but faces a number of environmental threats associated with urban development and human activities. The fast growth of Lima has exerted increasing pressure on the wetland ecosystem, with habitat fragmentation, land invasion and infrastructure construction close to the protected area [28].

Another important concern is water contamination. Untreated waste water from surrounding areas may be introduced into the wetland system, with pollutants, organic matter and other contaminants adversely affecting water quality and aquatic life. Furthermore, the build-up of solid waste such as plastics and other debris can also disturb the ecosystem and damage wildlife [11, 29].

These environmental pressures have the potential to alter habitat conditions, reduce biodiversity, and impact bird populations that depend on the wetland for survival. Hence there is a need for efficient monitoring to identify environmental changes and aid conservation efforts [12].

Considering the ecological importance of the Pantanos de Villa Wildlife Refuge and the environmental pressures that it suffers, it is necessary to make a permanent monitoring of the ecosystem. Monitoring programs can help to identify changes in biodiversity, to detect pollution or habitat degradation and to support the development of conservation strategies aimed at protecting the wetland.

Bird populations are particularly useful indicators to monitor environmental conditions as changes in their abundance or behaviour can be indicative of changes in habitat quality or ecosystem health. Conventional monitoring techniques, however, often depend on periodic field observations by researchers, which can limit the frequency and spatial extent of data collection.

Thus, the use of technological tools could improve monitoring in wetlands. These systems could allow for continuous data collection and more reliable information on bird presence conditions in the refuge. These approaches may be useful for conservation through an accessible and efficient way to monitor biodiversity in the Pantanos de Villa.

METHODS

The methodology consisted of four main phases: stakeholder consultation, data analysis and solution design, system development, and implementation and testing. The purpose of combining these elements in the methodology was to make sure that the suggested technological solution was in line with the conservation goals of the protected area.

Consultation and Problem Identification

Before designing and constructing the robot, consultation was made with site authorities involved in managing Pantanos de Villa. This was done in order to identify the main problems that the environment is facing right now, and whether the use of technology is feasible for monitoring this wetland.

After the consultation process, some of the main problems faced by the ecosystem were recognized as: changes in the hydrological cycle, increased human pressures on the buffer zones, degradation of habitats and isolated instances of poor water quality in certain sections of the wetlands. There were also noted changes in the number and type of migratory birds from year to year.

Furthermore, it has been suggested that the use of modern technologies in combination with traditional techniques will increase temporal coverage, consistency, and reliability of data collected regarding the ecology of the area under study, noting that such technologies remain consistent with the objectives of protection of the area in question. Special attention was paid to ensuring that no disturbances are caused to the wildlife especially aquatic animals and migratory birds which rely on stable water levels, safe breeding grounds, and reliable food sources.

Stakeholder Approval and Environmental Considerations

Being a protected natural habitat, the introduction of self-powered technological units should first undergo technical analysis and approval. As such, the robotic monitoring system that has been introduced was done following the technical principles set out by the guidelines of the general research project in the wetland.

In the initial system proposal, the use of the robotic system in terms of its functions, environment, and technical features was evaluated based on the goals of conservation of the wetland. Special emphasis was put on making sure that the robot would not interfere with the bird population, disrupt their nesting zones, or damage the ecosystem as a whole. As such, the system has been designed to be a floating robotic unit with low acoustic interference and without any stationary constructions in the wetland.

System Design

Accessibility, cost-effectiveness, sustainability, and appropriateness of the technology in terms of its ability to work in the wetlands were considerations taken into account when designing the robotically-controlled monitoring device. The structure of the floating unit was made out of pool foam tubes, offering buoyancy without including separate flotation devices. Not only does this reduce costs but also adds to the sustainability aspect of the project since common household products are repurposed.

A protective cover was placed on top of the foam tube frame to shield the electronic components from moisture, splashing, and environmental exposure, ensuring operational stability during field deployment.

The construction of the structural elements of the platform required that custom-made connectors be manufactured by FDM 3D printing technology. The printed parts ensured that the tubes would fit together properly and at an appropriate angle without the use of any adhesive or other connectors that might be adversely affected by moisture. Additional parts were made by 3D printing in order to accommodate the sensors; the custom-made mount for the camera would ensure that it stayed on one spot and had the same field of view over the surface of water in each of the monitoring periods.

Together, these fabricated components allowed the platform to be assembled in a modular and reproducible manner, facilitating maintenance, transportation, and field repairs when necessary.

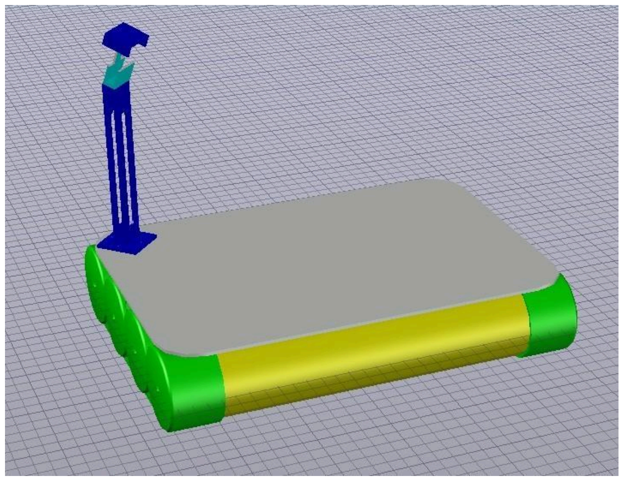

Figure 2: 3D CAD design of the floating monitoring platform.

Figure 3: Assembled floating robotic platform used during testing.

Power Supply

The power supply used to run the monitoring system consisted of two lithium-ion (Li-ion) batteries joined together in series formation, with each having a nominal voltage of 3.7~V and capacity of 1600~mAh. In the series formation of the batteries, the output voltage from the two batteries was 7.4~V, with the same capacity of 1600~mAh, thus resulting in the total energy stored being approximately 11.8~Wh.

The input voltage of the Arduino Mega varies from 7 V to 12 V due to the use of the built-in voltage regulator that steps down the voltage to 5 V required by the microcontroller of the board. With the battery giving an output voltage of 7.4~V, the battery can operate under the allowable limits of the Arduino Mega board without the need of using the external voltage regulator. The imaging subsystem was fed power from the Arduino Mega's 5 V output pin.

The selection of lithium-ion batteries was done based on their high energy density, lightweight nature, recharging capability, and consistent output of voltage levels, which would be beneficial for portable environmental monitoring devices. In order to ensure safe operation of the device in field conditions, the battery protection circuit was included into the construction of the monitoring device.

Data Collection

The process of collecting the data was performed using a two-element electronic system that consisted of an Arduino Mega microcontroller and an ESP32-CAM camera. The Arduino Mega was used as a central processing unit, allowing the communication between the sensors and the imaging module.

The HC-SR04 ultrasonic distance sensor was attached to the Arduino Mega and constantly monitored the surrounding environment by measuring the distance from the platform to other objects located around. The HC-SR04 has a nominal sensing range of 2–400 cm; however, for this study a detection threshold of 45cm was programmed to trigger image capture when an object entered the predefined monitoring zone. In this study, the ultrasonic sensor was used for detecting activity in the surrounding environment and taking images when an object appeared in the vicinity of the platform at a certain distance.

The ESP32-CAM module was chosen due to its built-in imaging features, small size, and power efficiency. The camera uses a wide-angle lens with an approximate horizontal field of view of 66° (OV2640 module), allowing the monitored area directly in front of the platform to be imaged. The serial connection between the Arduino Mega and the ESP32-CAM was made through TX and RX pins of both modules. Once an object was detected by the sensor and met the range threshold, the Arduino Mega sent a signal to the ESP32-CAM, and the latter took a picture.

The taken pictures were recorded onto a local storage (a microSD card placed inside the ESP32-CAM module), providing offline functioning of the module without requiring any network connections. Such a decision made it possible to increase the reliability of the system in the given wetland environment where network connection could be unreliable or absent.

Ultrasonic Sensor Characterization Testing

Prior to full-system deployment, the angular detection reliability of the HC-SR04 ultrasonic sensor was characterized independently through a benchtop test. A solid target block was positioned at a constant radial distance from the sensor and repositioned at a series of discrete angular offsets from the sensor's central (perpendicular) axis. At each angular position, repeated trials were conducted, and a trial was scored as successful if the sensor registered a valid return echo. Based on the pattern of results across angular positions, three angular reliability zones were defined: the main lobe, the fringe of the main lobe, and the side lobes. In parallel, camera trigger success was assessed by comparing the number of valid sensor-triggered events against the number of correspondingly captured images.

Implementation and Testing

After the setup of the system, the floating monitoring platform was released into action under controlled conditions within the wetlands. This was to determine the effectiveness of the buoyancy, the structural integrity of the system, the sensitivity of the sensors, and the efficacy of picture taking.

Careful consideration was taken to make sure that the system did not disturb any wildlife in the vicinity of the testing site. The design of the platform ensured that this monitoring system could work efficiently as a minimal invasion device and meet the ecological needs of the protected environment.

RESULTS

The robotic system shown previously in Figures 2 and 3 was used throughout all controlled and field testing. The goal of the testing process was to determine whether the robot could sense birds and capture their images in an autonomous manner and still remain stable in the aquatic environment.

Controlled Environment Testing

The controlled environment test was done to confirm the ability of the robot to sense the presence of birds and take images automatically. Food was placed on the upper part of the robot to lure the birds towards it, and the robot was then allowed to operate on its own with the ESP32-CAM continuously sensing the environment.

From the tests, the ultrasonic sensor was able to trigger the process of taking images when birds approached the robot. Some of the images taken during the tests are shown in Figure 4.

Figure 4: Representative images captured during controlled environment testing.

The timestamps recorded for the captured images indicate that the system maintained continuous operation and repeatedly detected the presence of birds throughout the testing period. Table 1 presents a sample timeline of image acquisition events.

Time	Observation
10:14 AM	Bird approached platform
10:43 AM	Bird feeding detected
10:47 AM	Additional bird detected nearby
11:38 AM	Bird approached platform
11:42 AM	Bird feeding detected
12:26 PM	Bird approached platform
12:41 PM	Bird approached platform
12:45 PM	Bird feeding detected
12:59 PM	Bird approached platform
01:07 PM	Bird feeding detected
01:18 PM	Bird approached platform
02:34 PM	Bird approached platform

02:50 PM	Bird approached platform

Table 1: Timeline of automatically captured images during controlled testing 1.

Detection Frequency Analysis

To provide an initial quantitative characterization of system performance, the event log in Table 1 was used to calculate the operational duration and detection frequency achieved during controlled testing. Across the continuous ~5-hour testing session, the system logged 13 discrete ultrasonic-triggered detection events, corresponding to a detection frequency of approximately 2.8 events per hour, or one triggered detection roughly every 23 minutes.

It is important to note that this metric characterizes the frequency and duration of logged trigger events, not a validated detection accuracy. Because an independent, synchronized human-observer record of bird presence was not collected in parallel with the automated system during this test, it is not possible to calculate true detection accuracy or false-positive/false-negative rates from the present dataset, nor to directly compare system output against manual observation. Collecting these validated performance metrics is identified as a priority for future work.

Ultrasonic Sensor Characterization

To quantify the directional detection reliability of the HC-SR04 ultrasonic sensor independently of the floating platform, a benchtop angular characterization test was performed. Table 2 summarizes the detection reliability observed within each angular zone.

Zone	Angular Range	Detection Reliability
Main Lobe	$0°$ to $\pm\ 10°$	100%
Fringe of Main Lobe	$\pm\ 10°$ to $\pm\ 15°$	$70\ -\ 90\%$
Side Lobes	$\pm\ 15°$ to $\pm\ 25°$	$10\ -\ 40\%$

Table 2: Ultrasonic sensor detection reliability by angular offset from the sensor's central axis.

Within the main lobe, a perpendicular target was detected on every trial. Reliability declined substantially at the fringe of the main lobe, where detection became inconsistent (70% - 90%) and often required multiple readings before a successful echo registered. Within the side lobes, detection reliability dropped further to 10% - 40%, indicating highly unstable performance in this region.

The region in which a bird would need to be positioned relative to the sensor to fall within imaging range spans approximately the main lobe and fringe-of-main-lobe zones. Because these two zones together provide reliability ranging from 70% to 100%, a bird positioned within the buoy's footprint will, in the majority of instances, be detected by the ultrasonic sensor. Detection within this footprint is not guaranteed, however. Overall, these results indicate that the sensor provides consistent, near-total detection reliability within a relatively narrow central cone, with reliability decreasing toward the edge of its effective detection range.

Camera Trigger Success Rate

During the controlled environment trials described, camera trigger success was assessed by comparing the number of valid ultrasonic sensor triggers to the number of correspondingly captured images. In all recorded instances, a valid sensor trigger resulted in a successful image capture by the ESP32-CAM module (100% camera trigger success rate). No instances of the camera subsystem failing to capture an image following a valid trigger were observed during these controlled trials.

Field Testing

This distinction is relevant to interpreting the absence of confirmed bird detections during the subsequent field deployment: because the camera reliably captured an image whenever the sensor registered a valid trigger during controlled testing, a missed image-capture opportunity is attributable to the ultrasonic sensor not registering a valid trigger than to a fault in the imaging subsystem itself.

Even though no direct interactions between birds and the robotic system were noted during field trials, there were indeed birds in the wetland environment around the system, with ducks swimming in close vicinity to the robotic system. This single field deployment therefore served primarily as a proof-of-concept trial for platform buoyancy, stability, and durability under real wetland conditions, rather than as a validated demonstration of autonomous detection performance in situ; the detection frequency figures reported are derived solely from controlled testing and should not be assumed to generalize to field conditions. Expanded field trials are needed to assess performance outside controlled settings.

Representative photographs of the field deployment are shown in Figure 5.

Figure 5: Robotic system deployed at Pantanos de Villa Wildlife Refuge.

DISCUSSION

The findings gained from controlled environment experiments as well as those collected from the platform implementation demonstrate the technical feasibility of using a cost-effective robotic system to autonomously detect and record birds within a wetland environment. This should be understood as an initial proof-of-concept: it shows that the underlying detection and imaging can function autonomously.

Scope of Demonstrated Capability

It is important to distinguish between the technical capabilities demonstrated by this study and its intended long-term environmental application. The controlled and field trials show that the platform can operate stably on water and autonomously capture images in response to nearby activity, demonstrating the feasibility of a low-cost, non-invasive bird-detection platform. However, this does not yet validate bird presence as a reliable indicator of environmental conditions. Establishing that relationship will require repeated field deployments combined with independent environmental measurements and comparisons with conventional manual bird surveys. Thus, this study should be viewed as a proof of concept, with environmental validation identified as the next stage of research.

Performance of the Robotic Monitoring System

A robotic system managed to integrate several subsystems of electronics and mechanics into one autonomous monitoring device. The ultrasonic proximity detector was able to detect movement and start the camera operation of capturing an image automatically, thus ensuring the possibility of acquiring information continuously without constant supervision of a human operator. During controlled environment testing of the system, bird activity was detected several times and images were acquired.

Also, the floating system demonstrated operational stability during the deployment in aqueous conditions. Recycled materials were efficient in keeping the system afloat as well as to provide adequate support for electronic devices.

Successful operation of the prototype is in line with findings from previous research emphasizing the increasing importance of automatic technologies in ecological observation [8, 9]. Like the system based on camera traps described in the literature review, the robotic system could collect biological observations without human participation. At the same time, unlike terrestrial camera traps that work in fixed position, the floating design of the system allows for operation in aquatic wetlands.

Bird Presence as an Indicator of Environmental Conditions

The relevance of birds as bioindicators of wetland ecosystem state is well established in the ecological literature [5, 6, 7], and the presence of ducks and other birds near the platform during field testing confirms that bird populations continue to use the monitored habitat. However, the present study did not itself collect environmental measurements (water quality, hydrology) alongside bird observations, so it does not directly test or validate the bioindicator relationship for this site; it demonstrates only that the platform can register bird presence, which is a necessary precursor to that broader application.

At the same time, some ecological interactions have been identified during the process of field testing which had an effect on the monitoring process. It is notable that ducks would often stay in proximity to the robotic system and thus prevent other species of birds from coming near to the area being monitored. In other words, the presence of some dominant bird species might have affected the composition of species being observed using this autonomous system.

Accessibility and Sustainability of Monitoring Technologies

A significant achievement of this study was showing how an environmental monitoring system could be created using rather inexpensive and easily obtainable components. In the course of developing the prototype, relatively inexpensive microcontrollers and sensors were used along with recycled building materials while providing an automated monitoring function at the same time.

Ethical Considerations

Ethical considerations are important when deploying autonomous technologies in protected ecosystems. The platform was designed to minimize wildlife disturbance by operating without continuous human presence and using a passive sensing strategy. An ESP32-CAM was selected because it produces no sound, and its flash was intentionally covered by the 3D-printed housing to eliminate visible light emissions. These design choices aimed to minimize disturbance, although future long-term deployments should continue evaluating any potential effects on wildlife behavior.

Contribution to Wetland Monitoring Research

The research is thus significant in the emerging area of robotic environmental monitoring through the examination of the use of a floating autonomous robot system developed for wetlands. Although there have been studies conducted on the use of drones, fixed camera systems, and complex robotic environmental monitoring systems, less work has been done regarding the use of floating robots for biological monitoring.

It is thus feasible to develop a combination of robotics and automation for ecological monitoring through such a system, though realizing that potential fully will depend on additional validation work.

STRENGTHS, LIMITATIONS, AND FUTURE APPLICATIONS

Strengths and Research Significance

A primary strength of this research project is the creation of a practical low-cost monitoring robot that can operate independently in wetlands aquatic environments. This is especially true when it comes to conservation efforts in developing countries where low funding usually means that advanced monitoring devices are not accessible.

This research project also makes an important contribution to the field of robotics for environmental purposes since it focuses exclusively on the floating platform for monitoring wetlands. Unlike the majority of studies which examine the application of aerial drones and camera traps on land, there are very few studies on compact floating robots for automated biological monitoring in aquatic environments [22, 23].

Other advantages include the non-invasive nature of the monitoring procedure itself. Because the platform can work in an autonomous way without people being nearby, it can potentially reduce any disruption that may be caused by the traditional method. The proof that birds could be monitored during the test proves that the use of robots for this purpose is possible.

Limitations

However, in spite of the potential value of its contribution, there exist a number of restrictions on the use of the system that should be taken into account while considering its results.

First of all, there are some limitations concerning the detection feature of the ultrasonic sensor. Though it helps to avoid the capturing of those pictures that do not represent any interest due to the absence of a flying bird, it is not able to differentiate between a bird and other objects or animals that can get into the area covered by the sensor, like floating rubbish, insects or small mammals near the water surface. Therefore, this leads to obtaining of the images that do not contain birds, which makes it necessary to conduct additional work for filtering the information received after the session is over.

In terms of the imaging capabilities of the ESP32-CAM module, there are several limitations that should be considered. Due to the presence of poor illumination, such as in the morning or on a cloudy day, the picture quality may decrease even more, making it difficult to use pictures that were captured in such situations. Thus, the system can be used mainly for recognizing the presence of birds but not for their identification in different environmental settings.

The life of a battery can be considered as another operational limitation. In view of the fact that the working time is only about five hours, the system is unable to work continuously without human assistance, which limits its capacity for performing monitoring activities. Thus, one of the main benefits of using automated monitoring systems is somewhat diminished due to the mentioned limitation.

Additionally, the field validation consisted of a single, short-duration deployment at Pantanos de Villa, so the reported detection results cannot yet be generalized to real wetland conditions, where factors such as platform motion, ambient noise, and variable lighting may affect performance. Although the study includes a characterization of the ultrasonic sensor and reports a 100% camera trigger success rate during controlled testing, true detection accuracy and false-positive/false-negative rates could not be determined without synchronized independent observations of bird presence. Repeated field deployments paired with manual observations are therefore needed to validate the system's real-world monitoring capability.

Future Applications and Improvements

There are multiple areas where this research can be developed further regarding the application of this robotic monitoring system. For example, the possibility to include other types of environmental sensors, which can measure different factors, such as water temperature, pH, turbidity, dissolved oxygen level, or conductivity. This will make it possible to complement the biological data with other information about the state of the wetlands' environment, thus, expanding the possibilities of system functioning.

Another possible area for development of this robot is the enhancement of its ability to identify birds in the environment. At the moment, the ultrasonic sensor is not able to differentiate between different species or locate the position of the bird. Better computer vision or sensing technologies would help to identify targets and minimize the impact of dominant species staying close to the platform all the time.

The development of artificial intelligence and computer vision technologies would provide additional improvements to the system through the ability to detect birds automatically and classify them based on the images captured [18, 19]. Machine learning algorithms will make manual image analysis unnecessary and help scientists more easily assess trends in biodiversity.

Further engineering improvements might consist of adding solar charging capabilities to increase system longevity, developing better stabilization measures to minimize motion due to water currents, and improving waterproofing.

A clear priority for future work is expanding field testing beyond the single deployment reported here. Repeated deployments across different seasons, or times of day would allow for direct comparison between the robotic system and conventional monitoring methods. Because further access to Pantanos de Villa was not possible within the timeframe of this study, these validation steps are identified as essential next steps rather than completed contributions of the current work.

Following the application of such platforms in Pantanos de Villa Wildlife Refuge, they can be used to conduct biodiversity monitoring in other wetlands, lakes, mangrove areas, and any aquatic environment that requires monitoring. Therefore, the availability of such monitoring technologies might help conserve these regions by monitoring them continuously in places where normal monitoring techniques have been difficult or expensive.

REFERENCES

[1] Environmental Protection Agency, “Why are Wetlands Important?,” *US EPA*, Jun. 13, 2018. [Online]. Available: https://www.epa.gov/wetlands/why-are-wetland s-important {epa2018}

[2] L. Feng et al., “Dynamics and Environmental Drivers of Wetland Ecosystems,” *Frontiers in Ecology and Evolution*, vol. 11, Art. no. 1123645, 2023. doi: https: //doi.org/10.3389/fevo.2023.1123645 {feng2023}

[3] Y. Zhang and X. Yan, “Ecological Modeling and Assessment of Threatened Wet-lands,” *Frontiers in Ecology and Evolution*, vol. 11, Art. no. 1296677, 2023. doi: https://doi.org/10.3389/fevo.2023.1296677 {zhang2023}

[4] D. Esenarro, C. Vega, and J. C. Rodriguez, “Urban Growth and Its Environmental Implications on Wetland Vulnerability,” *Urban Science*, vol. 8, no. 4, p. 156, 2024. doi: https://doi.org/10.3390/urbansci8040156 {esenarro2024}

[5] V. H. Dale and S. C. Beyeler, “Challenges in the Development and Use of Ecological Indicators,” *Ecological Indicators*, vol. 1, no. 1, pp. 3–10, 2001. doi: https://doi. org/10.1016/S1470-160X(01)00003-6 {dale2001}

[6] P. B. Landres, J. Verner, and J. W. Thomas, “Ecological Uses of Vertebrate Indicator Species: A Critique,” *Conservation Biology*, vol. 2, no. 4, pp. 316–328, 1988. doi: https://doi.org/10.1111/j.1523-1739.1988.tb00195.x {landres1988}

[7] W. Zhang and J. Ma, “Waterbirds as Bioindicators of Wetland Heavy Metal Pollution,” *Procedia Environmental Sciences*, vol. 10, pp. 2769–2774, 2011. doi: https://doi.org/10.1016/j.proenv.2011.09.429 {zhang2011}

[8] D. Tuia, E. Francis, and L. DeLeon, “Machine Learning Solutions for Autonomous Waterbird Monitoring: Innovations in Field Ecology,” *Journal of Field Ornithology*, vol. 94, no. 4, Art. no. 08, 2022. doi: https://doi.org/10.5751/jfo-00370-940 408 {tuia2022a}

[9] M. Budka, L. DeLeon, and D. Tuia, “Automated Acoustic Monitoring and Deep Learning Classifiers for Avian Species Identification,” *PLOS ONE*, vol. 17, no. 4, Art. no. e0266557, 2022. doi: https://doi.org/10.1371/journal.pone.0266557 {budka2022}

[10] E. Francis, M. Budka, and D. Tuia, “Remote Sensing Adaptations for Avian Distri-bution Surveys in Threatened Wetlands,” *Remote Sensing*, vol. 12, no. 7, p. 1185, 2020. doi: https://doi.org/10.3390/rs12071185 {francis2020}

[11] M. A. Gonzales, “Los Pantanos De Villa: Crisis Ambiental Por Mala Gestión De Residuos Sólidos,” *Infobae*, Sep. 17, 2024. [Online]. Available: https://www.info bae.com/peru/2024/09/17/los-pantanos-de-villa-crisis-ambiental-por-m ala-gestion-de-residuos-solidos/ {gonzales2024}

[12] M. Adam, D. J. Cooper, R. Jaunatre, J. Clement, and S. Gaucherand, “Wet-land Restoration: Can Short-term Success Criteria Predict Long-term Outcomes?,” *Restoration Ecology*, vol. 32, no. 7, Jul. 2024. doi: https://doi.org/10.1111/re c.14231 {adam2024}

[13] V. K. Chaudhary, D. Rani, and A. B. Toradmal, “Wetland Birds: Indicator of Healthy Ecosystem,” *ResearchGate*, vol. 978-81959483-83, pp. 195–198, May 2024. [Online]. Available: https://www.researchgate.net/publication/380998579_W etland_birds_Indicator_of_healthy_ecosystem {chaudhary2024}

[14] P. Marnn et al., “Modeling the Impact of Ecological Restoration on Waterbird Diversity and Habitat Quality in Myanmar’s Moe Yun Gyi Wetland,” *National Center for Biotechnology Information*, Apr. 08, 2025. [Online]. Available: https: //pmc.ncbi.nlm.nih.gov/articles/PMC12109046/ {marnn2025}

[15] C. Pan, S. Xu, Z. Qian, Q. Liao, T. Wu, and G. Wang, “How Do Waterbird Com-munities Respond to Multi-Scale Environmental Variables in the Satellite Wetlands Surrounding a Ramsar Site, Shengjin Lake in China?,” *Diversity*, vol. 17, no. 3, p. 176, Feb. 2025. doi: https://doi.org/10.3390/d17030176 {pan2025}

[16] V. Mitterwallner et al., “Automated Visitor and Wildlife Monitoring with Camera Traps and Machine Learning,” *Remote Sensing in Ecology and Conservation*, vol. 10, no. 2, pp. 236–247, Aug. 2023. doi: https://doi.org/10.1002/rse2.367 {mitterwallner2023}

[17] D. Guna-Tilaka, W. Sawangphol, T. Charoenritthitham, T. Kanjanapoo, T. Bura-sotikul, and K. Pongprasit, “An Acoustic Sensing System for Noise Monitoring and Source Identification using Transfer Learning,” *Expert Systems with Applications,* vol. 299, p. 130014, Oct. 2025. doi: https://doi.org/10.1016/j.eswa.2025.13 0014 {guna2025}

[18] M. A. Tabak et al., “Machine Learning to Classify Animal Species in Camera Trap Images: Applications in Ecology,” *Methods in Ecology and Evolution*, vol. 10, no. 4, pp. 585–590, Nov. 2018. doi: https://doi.org/10.1111/2041-210x.13120 {tabak2018}

[19] M. S. Norouzzadeh et al., “Automatically Identifying, Counting, and Describing Wild Animals in Camera-trap Images with Deep Learning,” *Methods in Ecology and Evolution*, vol. 9, no. 4, pp. 881–892, 2018. doi: https://doi.org/10.1111/2041-210X.12974 {norouzzadeh2018}

[20] F. Rovero and F. Zimmermann, Eds., *Camera Trapping for Wildlife Research*. Ex-eter, UK: Pelagic Publishing, 2016. [Online]. Available: https://www.researchga te.net/publication/301648058 {rovero2016}

[21] J. T. Fisher, “Camera Trapping in Ecology: A New Section for Wildlife Research,” *Frontiers in Ecology and Evolution*, vol. 6, p. 112, 2018. [Online]. Available: https: //www.ncbi.nlm.nih.gov/pmc/articles/PMC6102143/ {fisher2018}

[22] A. R. Smith and L. M. Jones, “Review on Robotic Systems for Environmental Monitoring,” *ResearchGate Technical Reports*, Jan. 2022. [Online]. Available: https://www.researchgate.net {roboticssurvey}

[23] K. Edwards and M. Torres, “Robots for Environmental Monitoring: Significant Advancements and Applications,” *ResearchGate Publications*, Jul. 2023. [Online]. Avail-able: https://www.researchgate.net {robotsenv2023}

[24] The Convention on Wetlands, “Los Pantanos De Villa — Servicio De Información Sobre Sitios Ramsar,” *rsis.ramsar.org*, Jul. 03, 2023. [Online]. Available: https: //rsis.ramsar.org/es/ris/884 {ramsar2023}

[25] Inca Trail Machu, “Los Pantanos De Villa: Get to Know the Key Protected Area for the Conservation of Birds in America,” *Incatrailmachu.com*, 2026. [Online]. Available: https://www.incatrailmachu.com/en/travel-blog/pantanos-de-villa-wildlife-refuge {incatrail2026}

[26] C. Calle, “Refugio De Vida Silvestre Pantanos De Villa, Lima,” *Perubirds.org*, 2024. [Online]. Available: https://perubirds.org/rutas_Pantanos_de_Villa.shtml {calle2024}

[27] J. Iannacone et al., “Diversidad De Aves En El Humedal Pantanos De Villa, Lima, Peru´: Periodo 2004–2007,” *Biota Neotropica*, vol. 10, no. 2, pp. 295–304, Jun. 2010. doi: https://doi.org/10.1590/s1676-06032010000200031 {iannacone2010}

[28] F. Almanza, “La Naturaleza a Merced Del Progreso: Los Pantanos De Villa Y Las Amenazas Que Representa La Urbanización En El Área Protegida,” *Conexión Ambiental*, Feb. 2021. [Online]. Available: https://conexionambiental.pe/la-naturaleza-a-merced-del-progreso-los-pantanos-de-villa-y-las-amenaza-que-representa-la-urbanización-en-el-area-protected/ {almanza2021}

[29] A. G. Losno-Prado and J. Iannacone, “Caracterizaci´on De Microplásticos En Agua Y Sedimentos En Los Humedales Los Pantanos De Villa, Chorrillos, Lima, Peru´,” *Bolet´ın De Investigaciones Marinas Y Costeras*, vol. 52, no. 1, pp. 185–194, Jun. 2023. doi: https://doi.org/10.25268/bimc.invemar.2023.52.1.1155 {losno2023}

[30] D. W. Ramirez and A. Cano, “Estado De La Diversidad De La Flora Vascular De Los Pantanos De Villa (Lima - Perú),” *Revista Peruana De Biología*, vol. 17, no. 1, May 2011. doi:

https://doi.org/10.15381/rpb.v17i1.58 {Ramirez2011}