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continued on the back inside cover

Cover: A bag worm with its beautiful heap of junk. Acrylics on 300 GSM paper by Dupati Poojitha based on a picture by Sanjay Molur.

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COMMUNICATION

Implementation strategy and performance analysis of a novel ground vibration-based elephant deterrent system

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Abstract: The establishment of human habitations, expansion of cultivation lands, and constant degradation of forest areas have intensified human-elephant negative interactions over the years in the Anaikatti area located at Coimbatore and Periyanaickenpalayam forest range in southern India. A few nature parks have been established in this interaction-prone area and are also affected by frequent elephant presence. To safeguard one such park, Nilgiri Biosphere Nature Park, from elephant and other wildlife intrusions, 13 units of a ground vibration-based 'elephant deterrent system' have been installed along its periphery. The system is a field-deployable version of our ground vibration-based 'elephant early warning system', designed to deter elephants using sound units upon detection. It analyzes the frequency of footstep vibrations to initially differentiate between elephant and non-elephant footsteps. The cumulative vibration data from sensors is then used to identify elephants more precisely. Furthermore, for certain system units, the system's algorithm has been adjusted via on-the-fly software updates to detect all animal footstep vibrations, activating deterrent sound effects tailored to the specific requirements of the current application. Insights from location surveys and discussions with local residents have contributed to the development of innovative implementation strategies and the careful selection of installation sites, which are detailed in this paper. The paper also outlines the system's installation layout, case-specific algorithms, and hardware architecture. Performance was monitored over an eight-month period, with the results analyzed alongside feedback from field observations. Notably, the system trial phase showed a reduction in elephant intrusions within the park. This report is the first detailed account of a trial field performance, making it a valuable reference for replicating similar solutions in other conflict locations.

Keywords: Human-elephant negative interaction, microcontroller, sensor string integration, signal conditioning unit, vibration sensor, warning system.

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Author contributions: SD—played a pivotal role in the development of hardware design, algorithm formulation, programming, and verification of field systems. RR—was responsible for conducting the field survey, overseeing the installation, and managing data collection. SKR—contributed significantly to the field installation process and the drafting of the manuscript.

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SERB Core Research Grant | NILGIRI BIOSPHERE NATURE PARK | BANNARI AMMAN INSTITUTE OF TECHNOLOGY Stay Ahead

INTRODUCTION

Over the years, several technologies and systems have emerged for human-elephant negative interaction management, but they come with their advantages and limitations (Shaffer et al. 2019; Vogel et al. 2020; Tiller et al. 2021). If categorized broadly, the technologies come in two categories: first, the elephant early warning system, and second, the elephant deterrent system (Choudhury 2010; Rohini et al. 2016; Tripathy et al. 2021). Although there has been notable progress in the domain of early warning technologies, very few successful non-contact elephant deterrent systems have been reported so far. (Nayak & Swain 2020; Feuerbacher et al. 2021). The high intelligence and adaptive learning capability of the elephant have restricted technologists from designing a long-lasting elephant deterrent system (Locke et al. 2016; MoEF 2020). The few reported short-term successful systems also had a lack of range, element of surprise, and have terrain-specific limitations (MoEF 2020).

Considering those technological ambiguities and urgent needs, our ground vibration-based 'elephant early warning system' (EEWS) was reconfigured into an elephant deterrent system, with a re-engineered system design, operational algorithm, control circuit, and addition of a high-volume hooter/siren. The EEWS was designed over the years with national and international funding (Ramkumar & Deb 2021). The EEWS was tested through simulated experiments, as well as with field implementation at Sathyamangalam Tiger Reserve in 2020 (Ramkumar & Deb 2021). With the feedback data from field-installed EEWS units, the technology was refined. With all those added attributes, the EEWS was re-configured into a ground vibration-based 'elephant deterrent system' (EDS). Under this work, a total of 13 units were installed to cover the 3.5 km periphery of the Nilgiri Biosphere Nature Park (NBNP).

Location Survey

Anaikatti is a small township near Coimbatore, located in the Western Ghats at the Tamil Nadu-Kerala border in southern India. Human activities such as agriculture, urbanization, and tourism are disrupting the traditional migratory routes of elephants. Additionally, the depletion of forest resources has forced elephants to explore new migration paths, making Anaikatti a key interaction hotspot (Karthick et al. 2016; A Times of India Report 2019; Deivanayaki et al. 2019). The intensity of the conflict is so severe that the area frequently makes news headlines and has been the subject of several research articles (Ramkumar et al. 2013; Natarajan et al. 2024). Being situated in this area, the Nilgiri Biosphere Nature Park (NBNP) has elephants visiting the site over the years. The NBNP is a nature-based organization designed to introduce and educate young minds about the unique flora and fauna of the Western Ghats, boasting a large collection of these species. The availability of food and water, especially during summer, has made the park an attractive entry point for the elephants.

To assess the elephant visitation scenario at NBNP, a detailed field survey was carried out on foot to accurately map the elephant movement paths. Additionally, key terrain factors such as soil conditions, ground slope, sunlight availability, and other parameters relevant to system installation were also surveyed. On the northern side of the NBNP, a hillside is covered in forest. To the east of the park, there is open land extending for about 1.5 km. This area features small patches of forest, scattered agricultural fields, and a few houses, as illustrated in Figure 1. Meanwhile, the southern and western sides of the park are covered by cultivation land and human habitation. There is a narrow footpath covering the three sides of the park, except for the western side, which is covered by a motorable road. According to local reports, the narrow path is utilized by cattle grazers, wood collectors, and farmers during the day, while at night, it becomes a route for deer, pigs, leopards, and other wildlife, including elephants. We interviewed a group of 50 individuals in and around the park, local forest officials, including park workers, to understand the status of interactions, map the movement paths of elephants & other wildlife, and analyze the intentions behind these intrusions, their frequency, distribution across seasons, and times of day. The survey was conducted during the first two weeks of August 2022, and the results are presented in Table 1.

The information from the general survey, presented in Table 1, indicates that over the past three years, a sub-adult male resident elephant and a mature migrating bull have frequented the site. The survey also reveals that the bull enters the area from November to April each year. During the day, elephants settle on the eastern side of the hill forest and visit the park and nearby villages after sunset. Despite the entire park perimeter being secured by an electric fence, it has proven insufficient to prevent elephant intrusions over the years.

Implementation Strategy

All potential entry and exit paths of the elephants have been marked on the map by analyzing ground conditions, gathering residents' feedback, and reviewing

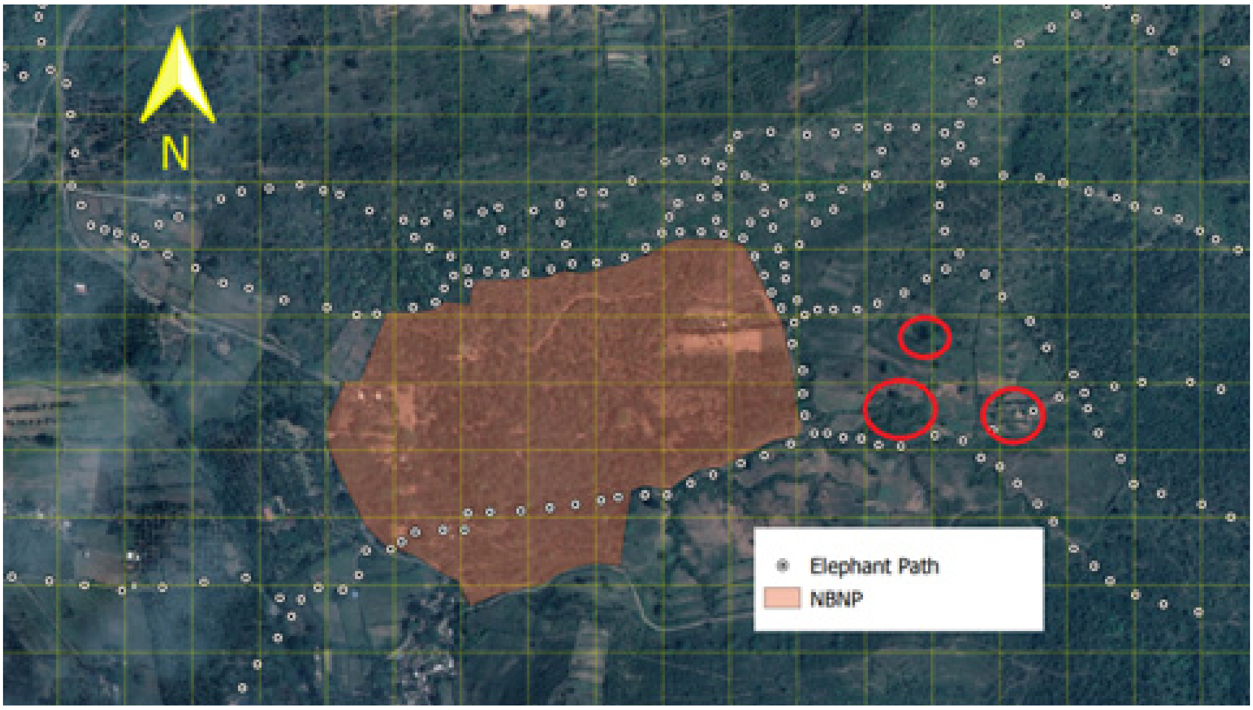

Figure 1. The satellite map of NBNP and the surrounding area, along with demarcated elephant paths and a few houses on the eastern side (marked with a red circle).

the survey report, as illustrated in Figure 1. It has been identified that most elephant paths from the northern and eastern sides of the park terminate at the boundary, which is secured by an electric fence. According to feedback from local residents and park workers during the field survey, once the elephants reach the fence, they walk along it in search of a weak point to breach the fence. Alternatively, they may continue their journey to reach the river and agricultural areas on the southern or western side. The survey also revealed that a narrow monsoon river runs through the southern section of the park, and during the dry months, this path is frequently used by elephants to access those destinations.

A comprehensive analysis of terrain conditions, vegetation, local infrastructure, animal species, the nature and direction of the visit, and other localized factors is crucial for designing and implementing an effective system to minimize visits. For instance, while we specialize in laser fence-based animal early warning systems, the steep slopes, dense vegetation, and the elephant movement paths along the park's electrical fence make such a solution impractical (Ramkumar & Deb 2022). Based on our survey and feedback from other project stakeholders, we have concluded that to effectively manage the human-elephant interactions in this area, it is essential to prevent elephant movement along the paths surrounding the park's perimeter. Therefore, we decided to install footstep vibration-based EDS units at the junctions where elephant paths intersect with the park's boundary. This solution is anticipated to be highly effective, as illustrated in Figure 2.

System Details

The EDS is a modified variant of EEWS with few added features, as described in the following sections with Figure 3.

System Hardware Architecture

The EDS is a two-sensor strings-based design, where one sensor string takes reference input from the other string to reject any common vibration. With two separate sensor strings, only one string captures footstep vibrations during a visit, while vibrations from rain, landslides, and vehicle movement are detected simultaneously by both strings. This allows the system to effectively distinguish and eliminate noise vibrations, responding only to footstep vibrations. The sensor string is designed with piezoelectric sensors in successive series and parallel combinations to optimize sensor string output in terms of both current and voltage. Two sensor strings are connected with the 'signal conditioning unit' (SCU), as shown in Figure 3. The signal conditioning unit is the combination of two identical 'pre-amplifier and filter sections' connected with each sensor data line

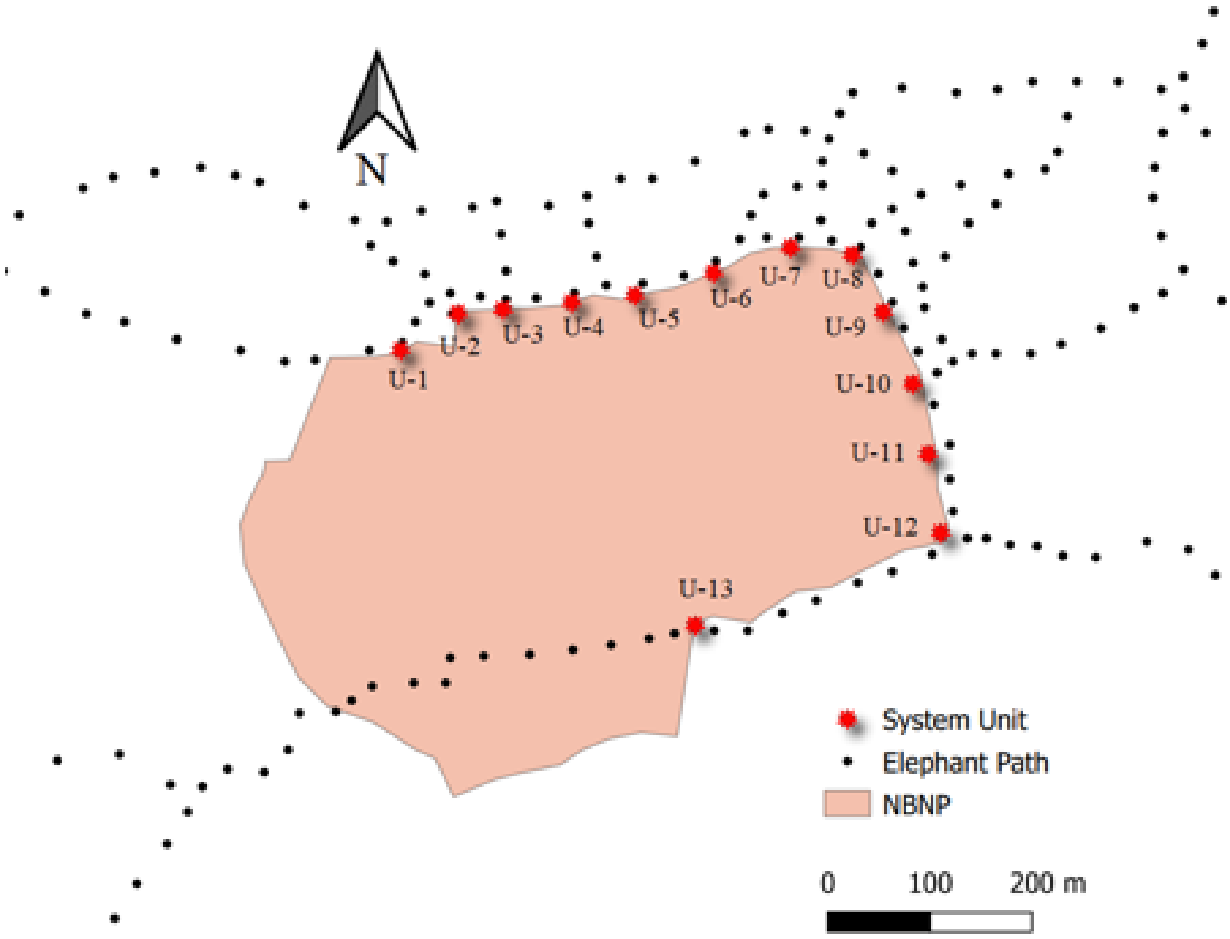

Figure 2. Elephant paths and placement of Elephant deterrent system units (U—1–U—13) along the park periphery.

Table 1. The conflict status survey. It involved a selected group of 50 individuals from NBNP Park and surrounding areas, including local villagers, park security, staff, and local forest officials. The sample was composed of 70% adult males, 20% children aged 7–13, and 10% females.

Questions	People Response
How many times has he/she seen an elephant in the past two years?	40% have not seen an elephant, 20% have seen one 1–2 times, 10% have seen it more than twice, and 30% have not seen it but felt its close presence.
What size was the elephant observed (adult, semi-adult, juvenile)?	70% reported seeing adults, 20% observed semi-adults, and 10% were unable to distinguish due to darkness.
During which season did he/she see the elephant?	80% of sightings occurred in summer, 5% in the monsoon, 10% in winter, and 5% could not recall the season.
At what time of day did he/she observe the elephant?	60% saw elephants during late evening, 30% in early morning, and 10% at midnight.
What was the likely path or track of the elephant's movement?	1. Did it bypass the park area and move toward the riverside? 40% of the time. 2. Did it go to the crop fields on the southern and western sides of the park? 25% of the time. 3. Did it intrude into the park area? 10% of the time. The remaining 25% were unsure.
What might be the cause of the elephant's intrusion?	1. Did it go to the river for water? 30% of respondents answered yes. 2. Did it raid crops in the agricultural land? 40% of respondents answered yes. 3. Did it go to the park area for food and water? 10% of respondents answered yes. The remaining 20% were unsure.

separately. The signal conditioning circuit of EDS is a design with few instantly configurable pot resistors, and thus its vibration sensitivity can be adjusted in real-time as per the terrain conditions and the target vibration. In a nutshell, the EDS can be configured into a highly sensitive mode to capture footstep vibration even from a house cat or extremely less sensitive, where it will sense the footstep vibration of large animals only. The authors have already analyzed the signal parameters for different animals footsteps and reported in (Ramkumar & Sanjoy 2021).

The control unit functions based on a microcontroller circuit. In this work, we utilized an Arduino-based microcontroller unit for decision-making, which is an open-source hardware and software component. The vibration patterns of various animals and humans are stored in the microcontroller. When the control unit receives processed signals from the SCU, it runs an identification algorithm and compares the input with pre-saved reference signal patterns. Upon detecting a match, the control unit activates the hooter to repel intruding animals. The basic identification algorithm has already been analyzed and documented by (Ramkumar & Sanjoy 2021), and the modified version used in the preset application is presented in detail in the following sections. The EDS operates on a 12-volt power supply and includes a stand-alone unit featuring solar panels (12V, 20W), charge controllers (12V, 6A), and batteries (12V, 2.5Ah). A daylight sensor is integrated into the system, allowing it to activate at dusk and automatically turn off at twilight.

System Implementation Design

In the current EDS design, each sensor string consists of four sensors, with each sensor spaced 1 m apart. The sensor string is buried at a depth of 20 cm and follows a zigzag pattern, providing a cumulative physical coverage area of 3 m² (calculated as 2 × 1.5 m²), as shown in Figure 4. However, once buried, each sensor has a vibration detection radius of approximately 2 m, making the effective sensing coverage area 2–3 times larger than the physical coverage area. When the sensor string is placed underground, it creates a detection field similar to an underground sensor carpet. The sensor string can be placed at a long distance from the hooter pole, providing a long detection range. The system is versatile and can be placed in various terrain conditions, except for waterlogged areas.

Placing the sensor string too deep can reduce its sensitivity but also help minimize background noise vibrations, so the depth must be optimized based on the terrain conditions and target species. The separation between two sensor strings (denoted as 'x' in Figure 4) must also be adjusted according to specific unit requirements. For this project, the maximum separation 'x' is 20 m for EDS Unit—10, while for EDS Unit—2, the separation between the two strings is 5 m.

In the current application, five types of 12-volt hooters are used across different system units in a random pattern, each producing a distinct sound to ensure sound diversity. The positioning of the hooter poles, the number of hooters, and their orientation are tailored to the specific requirements of each case.

System Algorithm

The system monitors three key parameters: 'signal frequency', 'signal amplitude', and the cumulative 'volume of vibration'. The EDS operates on a 10-second 'detection loop', controlled by a microcontroller (which aligns with the verified time an elephant typically takes to cross the sensor string). The flowchart shown in Figure 5 outlines the basic process for detecting and identifying elephants and other animals in the EDS. Previous simulated studies have indicated that elephant footsteps generate low-frequency vibrations, in contrast to animals with hooves, which produce higher-frequency vibrations above 100 Hz (Ramkumar & Deb 2021). This distinction is especially noticeable on rocky ground. After the signal is pre-amplified and filtered, the system algorithm checks the frequency input. If the frequency is identified as less than 100 Hz, it proceeds along the "elephant line".

Following frequency determination, the signal values are accumulated over a 10-second period, referred to as the "detection loop", and the resulting value is recorded as the 'cumulative vibration' (Vc). During each loop, the system checks for vibration peaks above a pre-set threshold. All amplitude values exceeding this threshold are accumulated within the loop to calculate the Vc. If the Vc is greater than or equal to the 'voltage elephant threshold' (Vte), the sound deterrent unit is activated to repel the elephant. This Vte has been determined from a previous simulated experiment with an elephant but also needs slight adjustment to counter the background noise of the implementing site. While humans and other soft-toed animals also generate low-frequency vibrations, previous observations show that their cumulative vibration values are significantly lower than the Vte, allowing them to be excluded when targeting elephants specifically.

This unique approach has been shown to achieve over 80% accuracy in detecting elephants through footstep vibrations, as confirmed by previous simulated

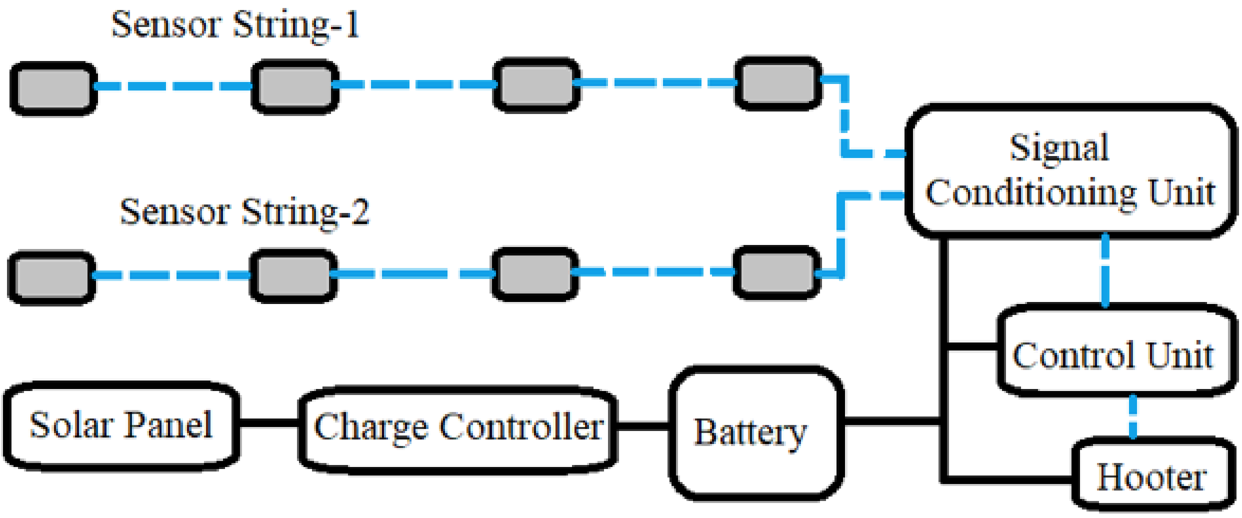

Figure 3. The internal hardware block design for Elephant deterrent system (dashed line are data lines and solid lines are power lines).

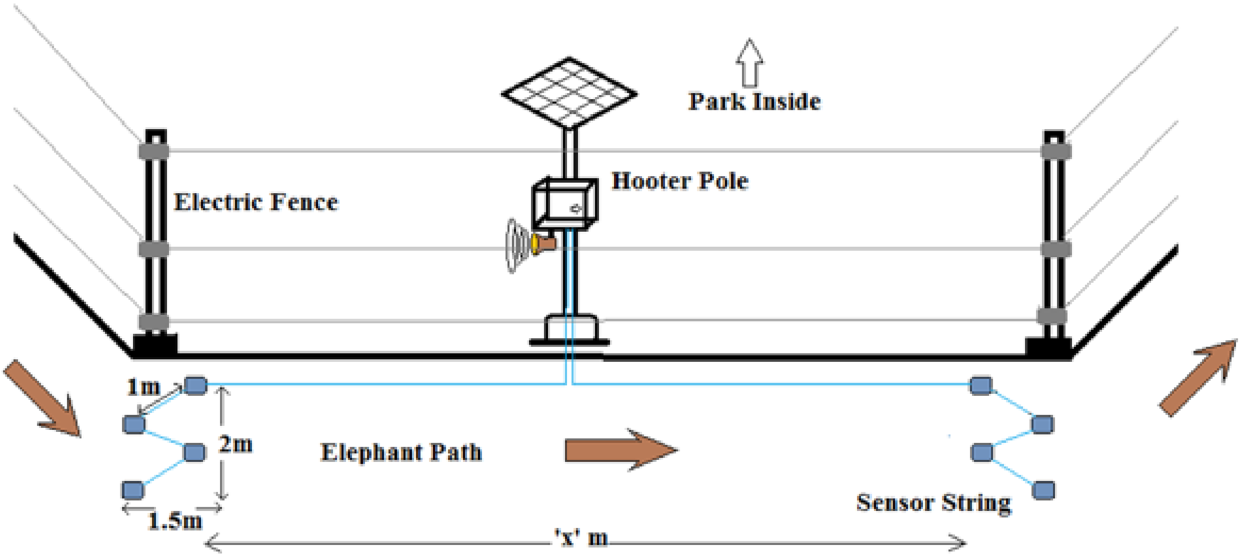

Figure 4. System field implementation architecture with hooter pole, sensor strings, elephant path, and existing electric fence.

experiments (Ramkumar & Deb 2021). The remaining 20% discrepancy in accuracy arises from system limitations in detecting elephants under certain conditions, such as muddy soil or loose sand, where sensor sensitivity is significantly reduced. In these situations, the system may incorrectly identify elephants and other animals. Additionally, high-volume vibrations from overlapping frequencies generated by a group of other animals crossing the sensor field could cause the system to misinterpret the detection as an elephant, leading to potential confusion.

To further distinguish elephant detections from those of other animals, the EDS employs distinct sound patterns. For example, when an elephant is detected, the hooter will sound continuously for five minutes to maximize the deterrent effect. This distinct sound pattern serves as an alert to park security personnel, prompting them to verify the potential elephant intrusion. In contrast, detections of other animals will trigger a one-minute sound with a five-second on-off pattern, ensuring different responses based on the type of detection. Considering our practical experience, the system algorithm is designed to trigger a maximum of 20 times per day, ensuring that contentious sound generation is avoided throughout the night, even in the event of a system malfunction.

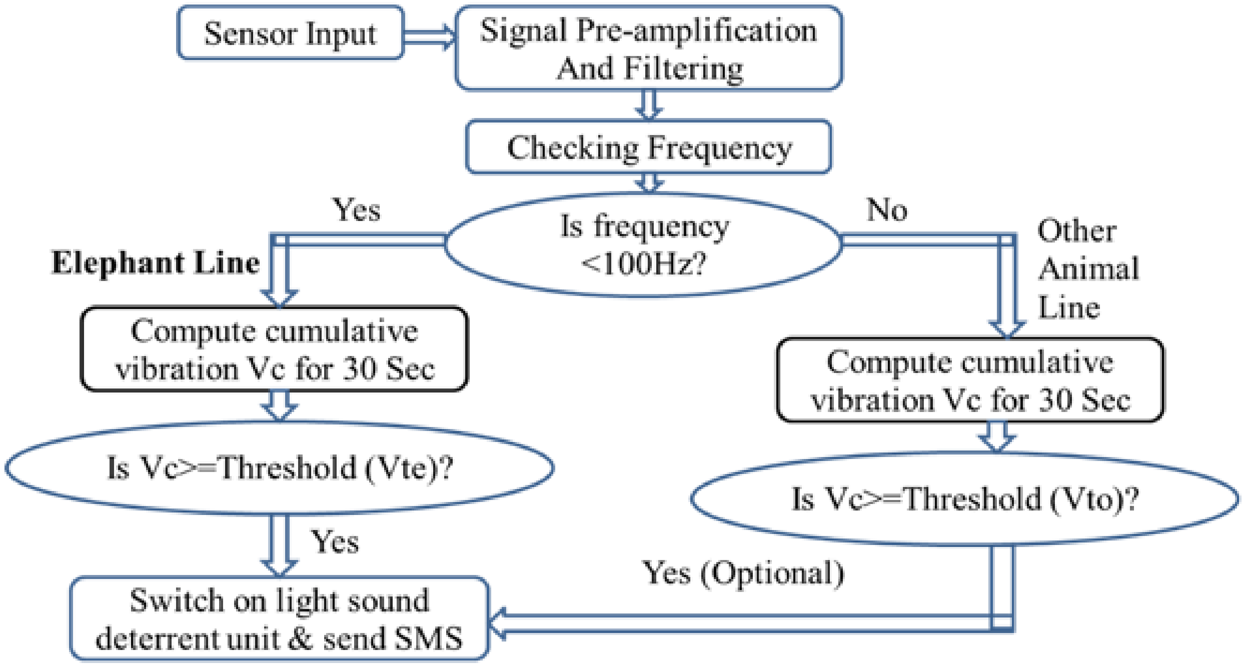

Figure 5. Elephant deterrent system algorithm flowchart.

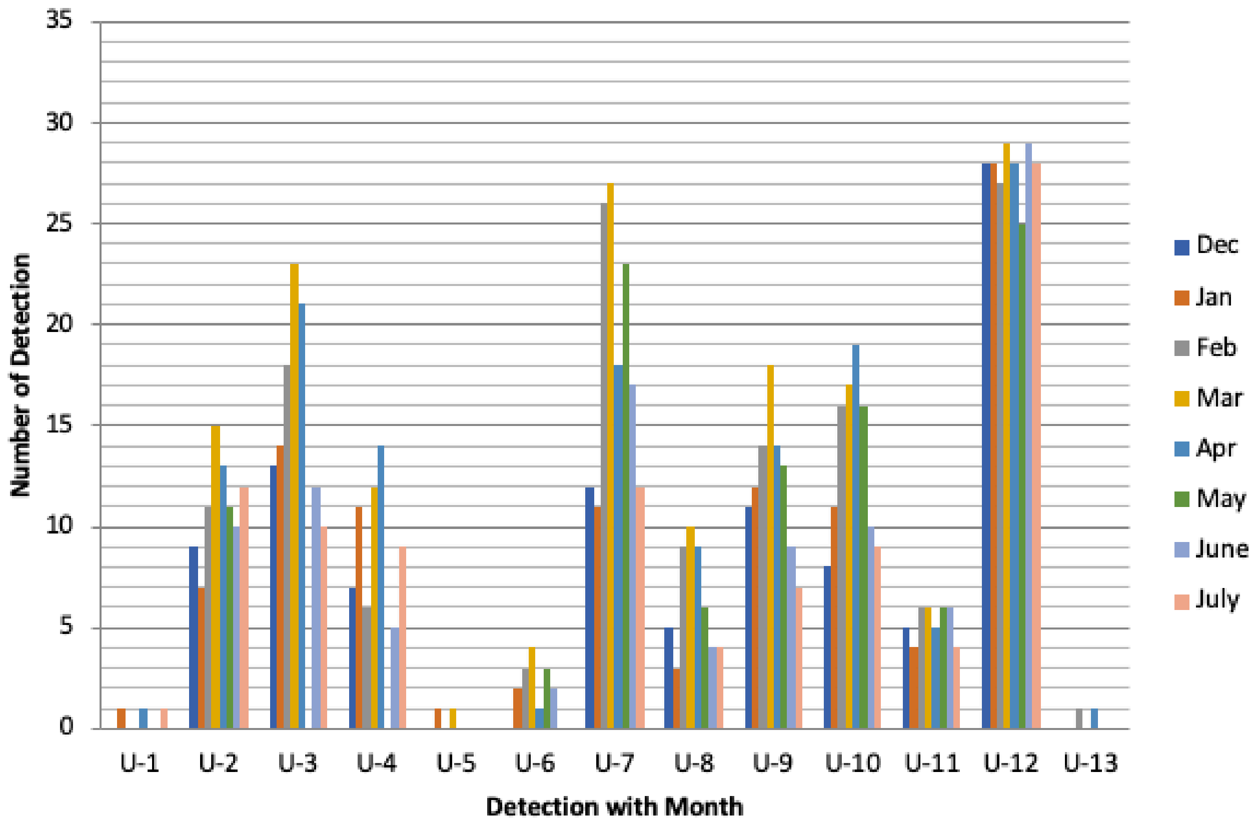

Figure 6. Elephant deterrent system unit-wise detection in months December 2022–July 2023.

System Performance Analysis

In October and November 2022, 13 EDS units were installed around the park perimeter. In addition to elephants, wild pigs, and spotted deer frequently visit the park, predating upon or uprooting plants including flower & vegetable gardens. Visitations are not limited to animals, as wood poachers have occasionally entered the park and poached valuable trees. To address these safety concerns, all units except Unit—1, Unit—5, and Unit—13 were configured in "all-animal detection" mode to reduce animal and human activity along the park's perimeter pathways at night.

As outlined in the algorithm flowchart, the EDS operates in two modes: 'elephant line', which detects and responds exclusively to elephant footsteps, and 'other animal line', which detects and responds to vibrations caused by various animals, including elephants. This enables the EDS to function either as an 'animal deterrent system' or an 'elephant deterrent system'. For trial purposes, Units 1, 5, and 13 were configured in elephant deterrent mode to evaluate their effectiveness, while the remaining units were set to animal deterrent mode to meet practical needs.

To create distinct sound effects, five types of horns and hooters were used with varying on-off patterns, ensuring unique sound signatures for each unit. Park security personnel monitored the system for eight months, recording unit-specific detections based on these unique sound patterns. During this period, the system was most frequently triggered by pigs, spotted deer, leopards, and humans, with elephants triggering the system only rarely.

The unit-wise EDS detection report for the eight-month period of December 2022–July 2023 is shown in Figure 6. According to our field observation report, based on input from local stakeholders, most detections were caused by wild animals and human activities, with only two instances involving elephants. Animal activity was found to vary seasonally; during peak summer, the scarcity of natural water and food sources attracted more animals to the park, where pump water holes are available at several locations. Consequently, most EDS units reported higher animal intrusions during late winter and peak summer.

A discrepancy was noted between the number of animal detections (total count of sound alarm) by the system and the actual number of animal intrusions into the park. This mismatch occurs because many animals bypass the park, using paths that lead to nearby villages instead. Notably, detections by Units 11 and 12 remained consistent throughout all months, later identified as being primarily due to human footsteps. To understand this pattern, time-wise detection data for all units was analyzed and is presented in Figure 7.

The survey revealed that most human outdoor activities around the park completely cease after 2000 h and resume after 0500 h. Except for three units, all other EDS units are configured to detect all animal modes. Thus, it can be inferred that detections occurring before 2000 h and after 0500 h are predominantly due to human activities. Most of the detections from units 11 and 12, located along human movement paths, occurred during these times, confirming them as human activity. Field investigations further revealed that several houses on the eastern side of the NBNP (marked with red circles in Figure 1) have residents who frequently use pathways near these units during those hours.

In contrast, other units primarily captured animal movements, which peaked before 2100 h, gradually decreased by 2300 h, increased again around 0300 h, and settled after 0500 h. This pattern may be due to animals moving towards nearby cultivation areas, villages, and rivers in search of food and water, especially as human activity is high in the evening and early morning. This aligns with the well-known pattern of animals raiding crops during late evening and early morning hours. Some units, like Unit 7, which are far from regular human pathways, recorded consistent animal activity during early evening, late night, and intermittently throughout the night.

The specially configured units (1, 5, and 13) did not detect any elephants during their runtime but did register a few false elephant alarms. The exact cause of these false alarms remains unclear, although no major technical malfunctions were identified. Elephant footsteps were detected on two occasions—at Unit 3 in January and Unit 8 in March. However, since these units were not configured in elephant detection mode, they produced sounds associated with other animals.

While no systematic statistical data exists on the exact number of elephant intrusions in the park over the years, discussions with staff and other relevant individuals indicate approximately nine visitations occurred in the three years prior to system installation. In contrast, following the system's installation, only one intrusion was recorded. This incident occurred during the peak north-east monsoon when many units were struggling with low battery issues, and the system failed to trigger an alarm.

According to park staff, elephants typically follow their habitual paths at night, testing the fence for weak points to enter. It is believed that the loud sounds triggered by

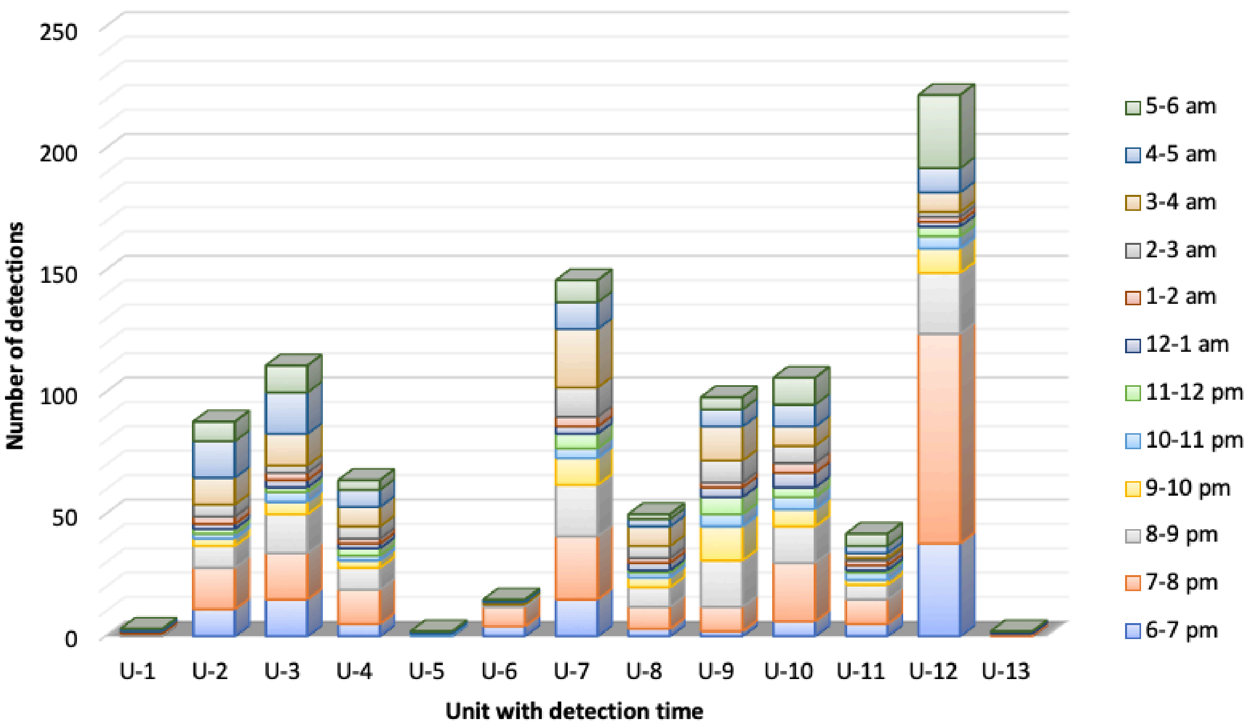

Figure 7. Elephant deterrent system unit-wise detection with different time phases during the night.

their footsteps, or the frequent sounds triggered by other animal movements, have discouraged them from using their regular paths along the park's periphery. Although the EDS has demonstrated a significant impact, its long-term effectiveness requires further validation, additional installations at other high-risk locations, and a detailed investigation into the underlying factors contributing to its success.

EDS Pictorial Representation

Figures 8–13 show some system-relevant pictures to help us better understand the EDS actual field architecture, infield performance, and other notable issues.

CONCLUSION

The ground vibration-based elephant deterrent system presented in this paper represents a pioneering approach and serves as the first trial report from India. This system is an advanced, field-implementable adaptation of the previously field-validated elephant early warning system technology. The paper provides a comprehensive description of the EDS hardware, field implementation strategy, and its innovative operational algorithm. This study documents the deployment of 13 EDS units in NBNP nature park and evaluates their performance over eight months. Additionally, it includes a field survey and subsequent analysis of conflict scenarios at the project site, accompanied by an accurate map of elephant movement paths. Such surveys and precise mapping are crucial for designing a strategic insulation plan, and the details shared in this paper offer valuable insights for similar projects. While the EDS is intended primarily to detect elephant footstep vibrations with precision, it has been optimized using a modified algorithm to enhance sensitivity, enabling the detection, and deterrence of other animals. This capability has been implemented and thoroughly reported in the current project. The system's performance analysis, which considers detection data across different times and seasonal variations, demonstrating that the EDS units effectively mitigate animal activities in the operational areas. By addressing the fundamental limitations of earlier animal-deterrent systems, the innovative EDS design has proven successful. The insights detailed in this paper provide a foundation for replicating this solution at other human-wildlife conflict hotspots, contributing significantly to the field once published.

Image 1. Interaction with locals during field survey.

Image 2. Preparing poles for installation.

Image 3. Installation of poles at selected locations.

Image 4. Digging the ground and placing the sensors.

Image 5. Field testing of system units.

Image 6. A fully functioning Elephant deterrent system unit with hooter.

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