Increasing the accuracy of rodent detection and estimation of the population with sensor fusion

Shrasti Dadhich
s2268205
Embedded Systems
s.dadhich@student.utwente.nl

***Abstract*—Rodents are the largest and most diverse taxonomic group of mammals, with over 2200 recognized species and recent estimates claiming the number to be close to 2500 [11]. A wide number of these rodents pose significant threats to agriculture, human health, and infrastructure. In this paper, we present a novel method for detecting and capturing rodents using a combination of sensor technologies. The detection and estimation of the rodent population are achieved using Radar sensors, while a Raspberry Pi camera and Ultrasonic microphone are employed to capture images and recordings of rodents inside the trap. PIR sensors are used to activate the radar, camera, and microphone when the presence of rodents is detected. To further classify the rodents, YOLOV4 and PointNet algorithms are used for object detection and point cloud classification, respectively. This method of trapping rodents is humane, and the classification of rodents enables the capture of certain useful species that can be reintroduced into ecosystems to perform vital roles in seed dispersal, soil aeration, and food chains. The findings of this research demonstrate the effectiveness of the proposed method by combining the sensor technology in detecting and capturing rodents while facilitating their classification for further research and conservation efforts.**

***Index Terms*—Sensor, Detection, Radar, PIR Sensor, Ultrasonic Sensor, Raspberry Pi Camera, Microphone, Raspberry-Pi**

I. Introduction

Every terrestrial area that supports life, whether it is wild, agricultural, or urban, has rodents. Rodents include species that are well-suited to arid environments and might thrive in all climatic zones. In general, warmer, wetter habitats tend to have a higher diversity of rodent species. These traits make rats more likely to coexist with humans in a free environment. This raises the damage caused to agriculture and human health. Their ability to adapt to habitats made rodents the best-suited mammals. It costs human health, agricultural industries, and even infrastructure. Despite the fact that rodents have beneficial effects on the environment, including soil aeration, mineral nutrient cycling, increased water absorption, biotic recovery, and the control of insect populations, they can also result in significant economic losses (primarily because they eat food that has been stored) and raise health risks by spreading various infectious agents to people [37]

The vast majority of crops farmed around the world, including cereal grains, vegetables, cotton, alfalfa, sugar cane, potatoes, tree fruits, and many others, are susceptible to damage by rodents. Rodents can change their preferred food sources during the plant life cycle, concentrating first on sown seeds, then on sprouting plants, and eventually on mature plants and their seeds/fruits, in order to adapt to the ecosystem [49]. Rats have the ability to fully destroy crop fields and occasionally stop planting where crops might otherwise be possible. Numerous rodent species can cause significant harm to grain crops like wheat, rice, sorghum, maize, and others all over the world. Crop damage levels can range from minimal (a few percent) to severe (>30%) to practically total crop loss. Rodent also affects the plantation crop. The movement of nutrients between the tree's roots and aerial sections can be disrupted by rodent damage, which also raises the risk of infection by root infections. Damage like this destroys trees, lessens fruit yield, and prolongs the time it takes for new plantings to start producing.[44].

In addition to the rodents causing damage to the crop in the harvesting stage, they can also cause severe damage to the crop in the storage i.e. post-harvest stage. This occurs from direct consumption, but also by contamination. Based on the survey conducted in Taiwan [10] More than half of the farmers (55.5%, n = 126) indicated rodents caused damage to their crops. About half of the farmers (49.2%, n = 126) indicated rodents caused damage to their crops during the pre-harvest or growing stage. Only 28.6% of participants stated that rodents caused damage during the post-harvest, or storage, stage for their crops. Each year, rodent damage to stored grain and field crops costs millions of dollars. For instance, the ”plague” of house mice in Australia in 1993–1994 cost the agricultural sector, the cattle industry, and rural areas around 60 dollar million in losses. If more effort were put towards lowering pre- and post-harvest crop losses brought on by rodents, Singleton and colleagues estimate that about 280 million undernourished people would benefit worldwide. Other types of damage from rodents come from their digging/burrowing which can undermine foundations and damage farm equipment and/or livestock passing by. Rodents can also damage wiring and insulation in buildings.

Some rodent species may coexist with humans as commensals, which can cause problems with sanitation, food contamination, property damage, and disease risk. As per the WHO, rodents can carry those infections and they can be transmitted between animals and humans (stated by WHO, 2012). Rodents can act as carriers of infection. The disease-causing agent is carried by the rodent, which exhibits no or few symptoms and can then be transmitted directly to humans. When their fur and feet come into contact with contaminated substrates while moving from one location to another, rats may also act as carriers of disease. Rodents pose a health risk because They have the capacity to intensify environmental infections and create (zoonotic) disease reservoirs ([47]). Rodents can transmit infections to humans directly, such as through bites, or indirectly, such as through tainted food or water.

Diseases are frequently linked with rodents due to the bubonic plague. Plague and the "Black Death," was one of the deadliest pandemics in recorded human history. Nearly a third of the human population died from this disease, and it is still spreading and causing illness and fatalities in some parts of the world [27]

All the facts stated above, clearly indicate that it is necessary to monitor the rodent population. There is various research conducted on the effective detection of rodents. The purpose of this study is to investigate whether emerging sensing technologies can be used to better detect and classify rodents. The field of animal detection is gaining importance due to its wide range of practical applications, such as preventing road accidents caused by animals, protecting residential areas from dangerous animal intrusions, controlling damage caused by increasing animal populations, and the behavior analysis of specific animals. Overall applications of animal detection can be classified into detection, tracking, and identification of animals. Various methods are utilized for animal detection, which are image processing-based systems, deep learning-based algorithms, and sensor-based systems. For sensory-based animal detection techniques, it implements working with PIR sensor, Ultrasonic sensor, and Radar. Deep learning techniques need to train the model on the detected object dataset. Image Processing based techniques use the processing of data camera images to identify and detect the animal.

This project aims to construct the SPYCE sensor-trap station to track rodent movement and gather data from various sensors in their natural environment (indoor and outdoor environments). The SPYCE will be a component of major sensory systems (radar/motion sensors) utilized for rodent impact monitoring and behavioral effect analysis utilizing computer-guided models. The Cyprus Municipality of Nicosia (/CYENS) will get the prototype.

II. Problem Statement

With the issue addressed in rodent increasing population, they are causing significant harm. there is a requirement for the effective detection of rodents and an estimation of the rodents population in the area. Although there has been considerable research on the topic of animal detection utilizing PIR and Ultrasonic sensors, the application to rodents especially is still emerging. For efficient and precise detection, it is necessary to combine multiple sensor technologies and validate the results.

III. Related Work: Detection of animal

A. *Literature survey-Animal Detection*

Animal detection has applications in lots of fields. When driving along country roads or intercity highways, chances are one animal or another will be met on the road. This increases the incidence of Road accidents. The animal-detecting device helps in saving lives and preserving livestock avoiding fatal accidents. There are several animal detection techniques that can be used for this application. In the paper by Atemkeng and Nandutu [32]Animal detection techniques have two approaches. The First is Area Covered and the Second is Break the beam. The system operates by reacting to changing physical conditions that interfere with its electrical properties. They capture stimuli such as heat, sound, and movements that animals induce. These stimuli convert to digital signals and are then sent to a computer for processing and analysis. Area cover systems are passive or active. Passive area cover systems are composed of passive infrared and video detection, and active area cover systems are composed of microwave radar

FLASH project by Gordon and McKinstry [20] is a system designed for the detection of deer on highways and notifying the drivers. It is composed of infrared sensors. Each moment a deer enters the detecting area, these sensors send out a signal that activates flashing lights. This model is tested day and night on a US roadway from October 18 to May 19. Together with an infrared sensor, a geophone unit detects ground vibrations brought on by animals crossing. Every time the geophone sensor is active, the camera is activated, and the entire crossing area is recorded. The average number of hits and deer per day for each month was calculated using information from the three different systems. In the project by Mukherjee, Sullivan, and Liu [30] LADS, it finds the animal in the vision and also sends the alert. It consists of two parts, one tracks huge animals as they approach the road and move through the monitored area, while the other alerts the vehicles. Radar detects animals when they enter the monitored area. The radar signal is examined by the processor, and identified as a huge animal. The driver warning system then turns on wirelessly linked flashing beacons.

In the project by Huijser [24] Doppler radar technology is utilized in 2017 to identify huge animals in a detection region and alert vehicles via triggered warning signs. They used thermal cameras to watch animals in the coverage area in combination with radar in order to test how well huge animals are detected. It also includes speed radars to track the speed of individual vehicles to asses the reduction in speed by drivers.

Another application for animal detection is the prevention and safety of animals. One of the research by Desholm and Mark [16] states the necessity to create a technique that could monitor the number of birds collisions with Danish offshore wind turbines. This gave rise to the project, "Development of a system for assessing collision frequency between migrating birds and offshore wind turbines." For the project, FLIR's IRMV 320V thermal camera is employed for reliable detection. A camera was put in a vertical position on a turbine rod.

The infrared camera's functionality is crucial at night time. With a thermal camera, birds could be spotted at a distance of 225 m during severe snowfall and 70 m during dense fog. It was able to record migrating birds approaching the revolving blades of a turbine, even in low vision.
In 2018, Shapoval and Lev [40] once again utilized Doppler radar to detect animals and people hidden by foliage. An HB100 sensor is employed by the Doppler radar. The radar will activate a detection if the strength of the reflected signal is lower than the signal that was provided in the first place. For testing, a dog and a person are also put behind the crops. In five out of every seven cases, humans are found, and in two out of every seven cases, a dog is found.

For the animal-vehicle collision system Break the beam is the second approach. As the paper states [32] Break the beam system works with the transmitter and receiver system with infrared, laser, and microwave radio signals. Transmitter's function is to send the signal to the receiver. Whenever the animal comes in between and breaks the signal it activates the warning sign to the driver about the animal.

Another application for animal detection is to monitor animal interference in the human habitat and to implement safety measures. In the research done by Vikhram, Revathi [7] it states that the animal inference is also caused in the farms. With the increasing population, there is a shortage of food and water in the forest area. This caused the increasing interference of animals in the farm and residential areas. Because of animal interference in agricultural lands, there is massive crop loss. It affects human life and property. The arrival of elephants and other animals has effects in numerous means like harming grain and destroying crops stores, water resources, homes, and other property. In one of the projects, For the detection, PIR and the ultrasonic sensor are used and they send the signal of the animal's presence in the field.

Another application for animal detection is used for Mowing operations. These days in the agricultural sector, much more efficient farming equipment is used. This grass-cutting equipment works with speed and it also increased the risk of the animal getting injured in the Mowing operations. While mammals, such as leverets of the brown hare (Lepus europaeus) and fawns of roe deer (Capreolus capreolus), have a natural instinct to lay low and still in the vegetation to avoid predators but using equipment increases their risk of being killed or injured in farming operations. This is especially true for ground-nesting bird species such as grey partridge (Perdix perdix) or pheasant (Phasianus colchicus) Many approaches are developed to reduce accidents in mowing operations. The paper by Sten, Kim [42], used thermal imaging to detect the chicken and rabbit in the grass. The thermal camera is used for recording the animal hidden in the grass. With digital processing, it detects the animal in the recording.

B. Literature survey-Rodent Detection

The above section survey findings give the background and overview of the animal detection applications. It also covers the different techniques used for animal detection. This section focuses on the research implemented for rodent detection.
In the research by the University of Tun Hussein [19] for the rodent population control in the paddy fields, PIR Sensor is used for the detection. In Asian countries, the dominant species in Peninsular Malaysia is the rice field rat (Rattus argentiventer) and Malayan woods rat (Rattus tiomanicus), the house rat (Rattus rattus diardii), and the large bandicoot rat (Bandicotaindica). With the rate of the rat population increasing, It is dangerous to the plantation and field. Farmers also lost more than 8% of the crop each season. The research [19] use the PIR sensor to detect the motion of rodent when they move in or out of the sensor range. Whenever the motion is detected, the output is high. Once the motion stops or the rat moves out of the range the output remains high for a few seconds. The device is a prototype to detect the rat by a sensor at a distance of 1m to 7m.

Physical activity is a critical parameter in many research and a rodent activity detector is a device built to monitor rodents.RAD is the research by Matikainen, Garmendia [28]is an open-source, cost-effective, device for measuring rodent activity. The battery-operated system is installed in vivarium home cages and allows for long-term, high-throughput operation with little help from the investigator. This study's main goal was to determine whether utilizing passive infrared (PIR) sensors with microcontroller-based dataloggers was practical. MSP430 PIR sensor is used. It has low power consumption. Data is collected by monitoring the 40 mice in the home cage. PIR sensor is useful to measure the movement over minutes.

Research by Castillo, Jana, and Giri [26] explain the effect of rats and pest in industry and home. A large amount of damage was caused to the crops, health, and storage. It develops the electronic pest-repellent device utilizing the PIR sensor and microcontroller as a processor.

House mice produce ultrasonic vocalizations (USVs) that are made up of a variety of syllable kinds and repeated repeatedly over time to create patterns of sequences. MUD is an algorithm by Zala, Reitschmidt [52] that automatically detects mouse ultrasonic vocalizations. At the Konrad Lorenz Institute of Ethology in Vienna, Austria, tests are carried out on wild-derived house mice (Mus musculus musculus). The Bioacoustic recorder takes the recordings. A-MUD detected substantially more true positives than the commercial software and significantly fewer false positives and false negatives, resulting in lower error rates.

In the paper by Sinelnikov, Sutin [41] it states the ability to acoustically identify and locate mouse movement by listening to their ultrasonic vocalization. This has been accomplished in a lab setting using an ultrasonic system with three microphones that can record ultrasound up to 120 kHz.It outlines the use of employing an ultrasonic microphone to find mice and rats. Three specially made microphones are utilized to record the rodents and mice for the test.

C. Literature survey for sensor

With the literature survey addressed above, it is clear that there are multiple projects and research for the detection of animals with different techniques. Now utilizing this knowledge, the section is defined to understand the specific sensors that could be used in the project. Based on the project conducted before an attempt is made to decide on the sensors for the project. This section outlines the available options and technical specifications of the hardware.

*1) **PIR Sensor**:* At temperatures higher than absolute zero (0 Kelvin / -273.15 °C), everything, including the human body, emits heat energy in the form of infrared radiation. Survey for animal detection and rodents detection shows the valuable use of the PIR sensor.

In the application by Vikhram, Revathi [7] animal detection in the Farm area is performed with a PIR sensor and an ultrasonic sensor. It used the PIR sensor HCSR501 providing the detection range between 5m and 7m with 5V power. When an animal enters the farm area, the PIR and ultrasonic sensor alert the controller with an input signal. The APR board will turn on instantly, and a sound is played to distract the animal. The flashlight will be on at night, and a call to the farmer and a message will be sent to the forest department.

This study [50] by Yusman Finawan and Rusali aims to design and construct a wild animal pest deterrent using a passive infrared (PIR) sensor and an ultrasonic signal, with a microcontroller acting as the system controller. The resulting repellant device can detect animals approaching up to a distance of 5 m and can potentially disrupt its hearing up to a distance of 20 m using a 40 kHz ultrasonic frequency. It used the PIR sensor HCSR501. Other considered experiments using PIR sensors are linked in the appendix for reading. As per the above survey, HC-SR501 is the PIR sensor used in the experiments conducted before for animal detection. Further details and research about PIR sensors are added in the Appendix section.
Below is the table I with the properties of the HC-SR501 PIR sensor. This information is used further to decide on the sensors for the project.

Features	HC-SR501
Sampling Range	within 7 m
Voltage	5V-20V
Power	65mA
Temperature	-15 +70

TABLE I
PIR SENSOR

*2) **Ultrasonic Sensor**:* An ultrasonic sensor is an electronic device that measures the distance of a target object by emitting ultrasonic sound waves and converts the reflected sound into an electrical signal.

In the paper by Yusman, Finawan [51], The objective of this project is to create a device that deters wild animals utilizing an ultrasonic signal and passive infrared (PIR) sensor, with a microcontroller serving as the system controller. The device uses ultrasonic waves to communicate at frequencies that are audible to animals.PIR sensors can detect living creatures that are in motion. The ultrasonic sensor also emits sound waves that make it difficult for wildlife to hear. This causes the animals to move out of range of the ultrasonic pulse.

Another project's by [8]primary goal is to prevent animal damage to crops while also diverting animals away. A system for detecting animals is intended to alert users of their presence. To track the movement of the animal and communicate with the controller, it used PIR and ultrasonic sensors in the project. By creating sound and a signal that is further transferred to GSM, it diverts the animal. This alerts the forest department and farmers right away. The 2cm–400cm non-contact measurement feature is offered by the ultrasonic ranging module HC–SR04 and the ranging accuracy is up to 3mm.

Finding animals trespassing on any agricultural or restricted areas is the project's main objective in the research by [12]. In this project, an ultrasonic sensor HCSR04 is used to estimate the target's distance, and a PIR sensor HCSR051 is used to detect a target's motion. A camera module on the detector is utilized to recognize animals, and it then displays the message on the LCD display.

Based on the literature it is evident that the HC-SR04 ultrasonic sensor is used for the experiments conducted for the detection of animals. Further details and research about Ultrasonic sensors are added in the Appendix section.

*3) **Microphone**:* In the wild, animals communicate by using smell, touch, movement, visual clues, and sound. As stated by [14] Ultrasonic vocalizations are the primary mechanism through which rats communicate with one another. When they make sounds, a frequency of around 20 kHz is linked to discomfort or suffering, and a frequency of around 50 kHz is linked to greater well-being.

There is a variety of recorders in the market such as Wildlife Acoustics SM4 and SM4BAT, Bioacoustic audio. With the increasing work on the ultrasonic microphone, it also explores the microcontroller for acoustic monitoring. Microcontroller-based developed recording options are an affordable way to acoustic surveys. It offers reliable, cost-effective solutions for simultaneous monitoring of both audible and ultrasonic frequencies. It brings to the development of the projects SOLO, Audiomoth, Aurita

Research by Beason, Riesch, and Koricheva [9] explores the gadget for Audible and Ultrasonic Recording with two separate recorders RPA2 bat recorder and SOLO. For the microphone, it used the EM-172 microphone and MEMS microphone. In the paper by Agranat, Ian [2] System used the Ultramic 384BLE microphone. It is capable of detecting the maximum frequency range of 190khz at a distance of 80m. It understands the condition of the bat's arrival near the turbines. The sound of the bats that are present near the turbines is captured using the microphone. The Raspberry Pi receives the signal if the bat comes closer than 100 meters, at this point the turbine will be shut off automatically.

SOLO is the research by Whytock and Christie [48] is made of the Raspberry Pi and the Clippy EM172 type FC049. It runs freely accessible and simple-to-install software. Bats emerged and foraged 3 to 4 meters above the Solo is monitor. Due to their small size, swift movement, and nocturnal lifestyle, bats cannot be directly observed. A multisensor system called a ”Bat Rack” [21] combines video camera records, automatic radio telemetry, and ultrasonic audio recordings into one modular unit. The audio module was implemented using Dodotronic Ultramic 384k hardware and the Raspberry Pi. The RPi Camera is used by the camera analysis module. Based on audio or VHF recordings, BatRack produces accurate occurrence information. Further details and research about microphones are added in the Appendix section.

Below is the table II with technical specifications for the microphone considered in the research conducted for animal detection discussed above

Features	Ultramic 250	EM172	M500 USB
Sampling Freq	250kHz	500kHz	250kHz
Freq Range	96kHz-192kHz	10kHz-160kHz	10Hz-160kHz

TABLE II
MICROPHONE

*4) **Thermal Camera**:* By measuring the infrared wavelengths, thermal imaging, also known as infrared thermography, transforms the resulting temperature data into visual images. The image shows a color tone that corresponds to the image's temperature range. In order to decrease wildlife mortality and consequently encourage farming, this paper In the work by [42] domestic chickens and rabbits were employed as study animals. This allows for the testing of feathers' insulative qualities, which reduces the heat difference between them and the environment. The recordings were made with an uncooled FLIR (Forward Looking Infrared) thermal camera. Due to the stronger thermal radiation from the animal than the grass, animals look brighter than the background.

Another application use of thermal cameras is Population estimation to understand the conservation and evolution of animal populations. Oishi, Hiroyuki's research [33] tested the DWA algorithm's capacity to automatically identify moving wild animals from thermal images. On the evening of June 10, 2010, a fixed thermal camera, the Thermo Shot F30, was deployed to record wild ducks in central Tokyo, Japan, at intervals of 30 seconds. It demonstrated a 77.3 percent increase in accuracy. The current study by Franck, Marie, [45] shows how the camera tool is useful for a variety of research areas, including animal behavior, population monitoring, and fauna-flora interactions.

Below is the table III with the technical specification of the thermal camera referred to in the survey. There are also multiple projects conducted with the raspberry pi camera for animal detection. It has an infrared LED which supports night vision. The IR LEDs are powered directly from the CSI port and are capable of lighting an area at a distance of up to 8m. This is the standard version with a 75.7 degree Field of View. Raspberry Pi night vision camera uses the OV5647 and it delivers a 5MP resolution image.

Features	FLIR One	FLIR C5	Raspberrypi
IR Sensor	160*120	160*8120	1080
FOV	54*42	55*43	75.7
Image Freq	8.7Hz	8.7Hz	8.7Hz
SDK	Atlas	FLIROne	Raspberrypi

TABLE III
CAMERA SPECIFICATION

Below is the table IV with the technical specification of the considered Raspberry Pi camera-Night Vision IR cut

Features	IR-Cut Camera
Sensor	5 megapixel
Focal Length	3.6mm
Aperture	2
Resolution	1080p
Angle of view	50 degree

TABLE IV
RASPBERRY PI CAMERA

*5) **RADAR**:* RADAR, short for ”Radio Detection and Ranging,” is a technology that uses radio waves to detect, locate, and measure the distance, speed, and direction of objects. There is an increase in the need for the automated quantification of animal behavior. For automated tracking, FMCW radars are proposed for the large diversity of animals.

As stated by Van Raalte in paper [36], the IWR1443BOOST FMCW Millimetre Wave Radar from Texas Instruments was utilized in this study to collect data from the test subjects. The range, velocity, and angle of an object are recorded with reflected signals. The operations were carried out at a distance of 1.30 meters from the radar, which was fixed on a tripod at a height of 0.90 meters. It records animal activity and human activity.

Radar application is utilized in automatic driving also. To find a collision-free path, the obstructions, and relative velocity must be detected, and information about the surroundings. The majority of manufacturers of autonomous vehicles rely heavily on RADAR and LIDAR. These systems function in all types of weather, including fog, rain, snow, and dust. In this study, [25] a methodology for measuring the range and coverage angle of the RADAR sensor AWR1642 in various configurations is proposed. Testing for the RADAR is done on actual vehicles. The results show that RADAR can accurately detect medium-sized objects at a distance of 50 m when certain parameters, such as best range and best range resolution, are tuned properly.

In the test by Texas Instruments[1] to determine the maximum range and detection by the IWR1642 radar. Tests are conducted on a single small car and a motorcycle driven away from the system. The results were logged. It is concluded that radar can detect a bike at a distance of 50m and detect a car at a distance of 80m. The IWR1642 is a specific type of radar sensor developed by Texas Instruments. It is part of their mmWave (millimeter-wave) sensor portfolio and is designed for short-range radar applications. The IWR1642 radar sensor operates at a frequency of 76-81 GHz, which falls within the mmWave frequency range, and it utilizes the frequency-modulated continuous wave (FMCW) radar technology. The IWR1642 radar sensor is capable of providing high-resolution range, velocity, and angle measurements of objects in its field of view.

Documentation by Texas Instrument on the radar AWR1843 [6] testing of the AWR1843AOP EVM was employed. At the top of the vehicle, the EVM was positioned vertically with the USB port. In this test, radar is used in the short-range (10m–50m) to recognize bicycles, pedestrians, and cars. It indicates the detection of the car to 40m and pedestrian to 15m. Using the ultra-short range (0m–10m) sub-detection frame's capabilities, the Same test is run to look for objects including traffic cones, shopping carts, sign poles, pipelines, and plants. The maximum distance is 8m and the minimum measurement is 4m.

RadrIQ is the FMCW sensor. It operates on the 60-64Hhz frequency. The range of the radar is 40mm to 10,000mm. As per the details shared in [38], it has a 110-degree azimuth field of view and a 15-degree elevation field of view. It also allows focus on the desired area with variable FOV With the scene calibration tool data may be easily cleaned up to remove any interference from enclosures and other nearby equipment. Radar functions effectively in outside environmental circumstances. The 'remove static objects' filter allows the sensor to focus just on movement and ignore anything in the background. In order to enable the sensor to produce findings of greater quality, the point density filter is kept too dense. It shows the application in the detection and tracking of objects with point cloud mode and tracking mode respectively. Based on the literature survey, below is the table V with the Texas instruments radar considered in the research.

Features	AWR1642	IWR1642	AWR1843
coverage	76-81Hz	76-81Hz	76-81Hz
Transmit	2	2	3
Receive	4	4	4
Temp	40C	-40	-40
MaxTemp	125C	105C	125C
Power	12dBm	12.5dBm	12dBm
Distance	50m	80m	50m

TABLE V
MM WAVE RADAR

Below is the table VI with the technical specification for the RadarIQ product

Features	RadarIQ
coverage	60-64Ghz
FOV	110Degrees
Ver FOV	15Degrees
Distance Resolution	40mm
Range	0-10m
Power	5V 0.38 Amp

TABLE VI
RADARIQ

D. Literature Survey For Trap Design

With the above-conducted literature survey, understanding is drawn for the components that could be used in the project. Technical specifications and availability of the hardware are considered for purchase. For the deployment of the project trap prototype needs to be built. This section explains the literature survey conducted for the trap model.

There are multiple traps deployed in the market for the detection of rodents. It also compares the performance of the trap with respect to the habitat. How rodents behave to the specific food bait. Below listed is some literature that captures the performance of the trap designs. These observations will be utilized in deciding the design of the project.

The paper by Yoav, Yotam [29] explains a thorough study that compared the effectiveness of 11 different trap designs (seven live and four lethal) in capturing various species of tiny rodents. The investigation was carried out in plantations and agricultural areas located throughout Israel's diverse geographical regions. Mice (Mus musculus), rats (Rattus rattus), as well as other species like jirds, voles, and shrews, were captured in the trap. These mice and rats are also found in Cyprus.

Based on the result of the overall performance of the trap. Result plot 1 demonstrates that Victor Mouse's detection comes first, followed by Sherman's trap. Given the requirement of the project, Victor's mouse trap design is not applicable. As victor mouse trap is designed primarily to catch and, usually, kill rodents. It is invasive and against the animal welfare

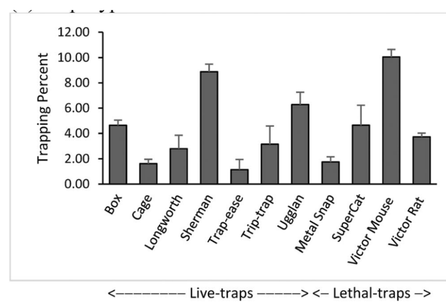


Fig. 1. Trap Type Comparison

For the mice as seen in the result figure 2, the Sherman trap came in second place for mice, followed by the Box live trap in third place, the Victor Mouse in fourth, and the Victor Rat trap in fifth place.

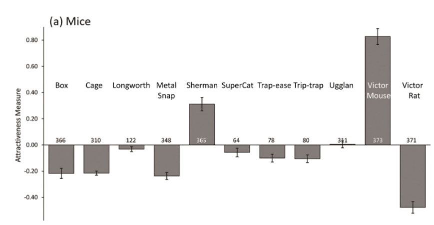


Fig. 2. Trap Comparison For Mice

Pairwise comparisons were performed only between the four most abundant traps—Victor Mouse, Box, Victor Rat, and Sherman. The performance of the Sherman is second to victor mouse.

Researchers divided crop types into three categories for the purpose of analyzing the impact of crop type on the attractiveness to mice of the four most common traps: cereals (which are primarily wheat), field crops (alfalfa and other legumes, potatoes, vegetables, and other field crops), and orchards (avocados, citrus, dates, deciduous, olives) Below is the result figure 3, which shows Sherman trap performs detection on the following crops This evidently shows that a

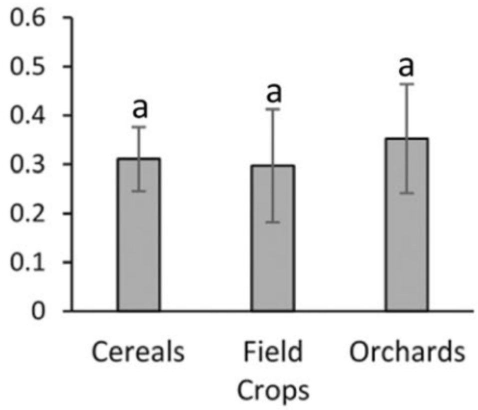


Fig. 3. Crop Comparison

design similar to the Sherman trap could perform the detection on the crops, which are also most affected in Cyprus.

This paper also gives the opportunity to understand the performance of the trap in the habitat. Based on the result, it is evident that the Sherman trap can perform in a habitat similar to the northern valley

From the survey results, it is clear that the Sherman trap is effective for rodents and mice. Further, The objective of this study [5] was to assess the relative effectiveness of Sherman traps, including small and big folding traps, and Longworth trap types for capturing small mammals associated with grasslands. The dimension of the small non-folding Sherman trap is (17.0 cm x 5.4 cm x 6.5 cm) and the dimension of the large folding Sherman trap is (23.0 cm x 7.7 cm x 9.1 cm). Dimension of the rodents captured in the traps are western harvest mice an average of 13cm jumping mice an average length of 180- 240mm, prairie deer mice 9.6cm

Finally, there is a study to compare the different designs of the Sherman trap size. This is important to understand which dimension is useful for the rodents found in Cyprus. In the study by Quast and Howard in 1953, the effectiveness of two sizes of the well-known Sherman live trap in catching three kinds of mice. deer mouse with dimension 9.6cm, pinyon mouse with dimension 171-231 mm, And brush mouse have a head-body length of 86 to 105 mm (3.4 to 4.1 in) was compared. Although the smaller traps actually managed to capture 42% of the much larger kangaroo rats, the larger traps nevertheless managed to capture roughly nine times as many mice.

With the details given in these papers, it could be compared with the Sherman trap size and rodents in Cyprus. Rodents in Cyprus [35]

- The largest in size known as Rattus Norvegicus, they are 30-50 cm long with a tail length less than that of the body, an average from 15-25 cm.
- Rattus Rattus or the roof mouse have 16 and 22 cm in head and body length and a tail length of 19 cm or longer.
- Mus Musculus is known as a domestic mouse. The total length of the mouse body is 160-200 mm
- Acomus Nesiotes, is the field mouse with 15cm and height 2.6cm.

It clearly indicates that the size of the trap should be more than 30cm *8cm*9cm

Firstly Trapping arrangement is compared. Eight Trap line is established for a total of 464 days. The average number of rats trapped was 12.40. There were a total of 51 rats and no mice captured over the 464 trap nights for each type of trap. Below is the result figure 4 to define detection by trap line arrangement

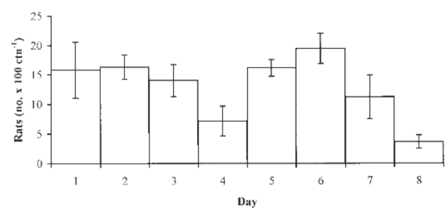


Fig. 4. Detection by Trap Line

A trap grid is set up covering an area of 12.25ha. There were 21 rats and 5 mice captured in total over the two grids. Rats were more commonly caught on the grid's other lines than mice, which were all caught in the grid's center. Below is the result figure 5 to define detection by trap grid arrangement

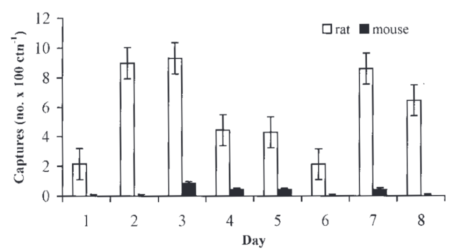


Fig. 5. Detection by Trap Grid

Rodents were shown to feed on all five different varieties of bait. While others were chewed, some cubes were totally consumed. Cheese, chocolate, soap, wax, and oiled wood were the top five favorites (chewed and eaten). Below is the figure 6 with result to define which bait is more useful

To the above-stated facts, it is useful to understand the external factors for the performance of the trap.

- Sherman trap design is ranked first for rodent detection
- Sherman trap has two trap design dimensions. Given the average size of the rodents in Cyprus. A large dimension of 30cm*8cm*9cm is effective for detection.
- Sherman Trap design performs for Field crops and cereals. Mostly crops and cereals are attacked by rodents in Cyprus

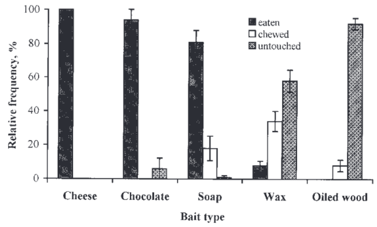


Fig. 6. Bait Type Comparison

- Sherman Trap performs major detection rate in valleys and plains. The main features of the Cypriot landscape are hilly fields, fertile plains, forests in the mountains
- Trap grid, and Trap Line arrangement. For multiple deployments of the model, trap grid design arrangements could be considered.
- Bait traps are effective for attracting rodents in the trap. Cheese and Chocolate could be considered for the trap

IV. Research Question

How can we increase the accuracy of rodent detection and population estimation by means of emerging sensing technologies?

A. *Sub Research Question*

- How accurate a radar estimates the rodent population in a given area
- How the integration of multiple sensors provides detection in the short-range
- how to achieve accurate and improved detection with modification in parameters
- How to perform identification and classification on rodent

V. Methodology

After conducting a literature survey on the individual sensor, it is feasible to compile a list of hardware alternatives for detecting animals. By taking into account the project requirements and comparing the specifications of each option, the most suitable hardware is chosen for the project.

A. *Requirement For Hardware In Prototype*

Given the project, there is a certain requirement with the hardware for effective and accurate operation. Below is the list of the requirements considered for the project

- Should be able to detect rodents in some field/area, at distances between 5-50 meters
- Should be able to detect if some of those rodents enter the trap
- Should be able to detect if some of the rodents eat the bait inside the trap
- Should be able to detect the instinct of the rodent.
- Should be able to record the activity of interest in space and time
- Should be able to estimate the rodent population in the nearby area, e.g. count up to 5-10 rodents simultaneously
- Should combine a range of sensing technologies to increase the accuracy

In the survey of sensors, a list of proposed hardware is built. Now to finalize the hardware, it is important to link the individual requirement with the hardware options.

1) PIR Sensor
   Requirements that could be covered
   - Should be able to detect if some of those rodents enter the trap
   - Should be able to detect when a rodent is near the trap
   - Estimate count of the rodent near the trap

   Based on the literature found, most of the detection of animal projects is conducted with the PIR sensors HC-SR051 within 5-6m. Detection of rodents around the trap could be completed with a PIR sensor.
2) Ultrasonic Sensor
   Requirements that could be covered
   - Should be able to detect if some of those rodents enter the trap
   - Should be able to detect when a rodent is near the trap

   These requirements are already covered with the PIR sensor. Placing the ultrasonic sensor inside the trap could also affect the performance of the camera.
3) Infrared Camera
   Requirements that could be covered
   - Should be able to detect the instinct of the rodent.
   - Should be able to record the activity of interest in space and time

   Based on the survey and requirement, it is clear that Thermal cameras are modeled to study the heat and temperature of the animal. The requirement for the camera in the project is to observe the activity of rodents near the bait.
4) Microphone
   Requirements that could be covered
   - Should be able to record the activity of interest in space and time
   - Monitor the position of rodents

   For recording the movement of the rodents, it is useful to record the voice of the rodents. As stated in the survey above, there are multiple projects that focus on the importance of microphone recordings to understand the behavior of rodents.
5) Radar
   Requirements that could be covered
   - Should be able to detect rodents in some field/area, at distances between 5-50 meters
   - Should be able to estimate the rodent population in the nearby area

As evident from the survey, Radar increases the detection range and it is also not required to implement a tag on the animal. Radar is widely used in various fields, including aviation, navigation, meteorology, military, and scientific research, for a wide range of applications, including monitoring and tracking objects or phenomena of interest. Radar works without getting affected by environmental and weather conditions.

B. *Selection Of Hardware*

1) PIR Sensor: With the survey for the PIR sensor, it shows that detection of the animal is performed with the HCSR501.In the research by the University of Tun Hussein [19] for the rodent population control in the paddy fields, PIR Sensor is used for the detection. The prototype detects the rat by a sensor at a distance of 1m to 7m.
2) Infrared Camera: For the Raspberry Pi [3] A superior version of the RPI camera (B), the raspberry pi IR-CUT camera offers both Normal and Night Vision modes. Its lens can be adjusted for focus, and the IR-CUT filter is detachable from the module. Infrared LEDs are also included to enable night vision. It may be utilized for object recognition and high-quality wildlife photography because the focus is changeable. It is easy to integrate with the raspberry pi and also fulfills the requirement of the project
3) Microphone: Given the literature, there were multiple microphones available in the market for bioacoustic monitoring. But given the aim microphone should be compatible with Raspberry Pi also. With the given option Ultramic and M500 USB are the best-suited microphones. the microphone is sensitive, with a good signal/noise ratio and a small form factor
4) Radar: Accurate measurements of an object's range, velocity, and angle were enhanced. IWR1642 detect Objects up to 84m With a Range Resolution of 37 cm. It offers an Antenna Field of view ±60º With an Angular Resolution of Approximately 15º.RadarIQ is the second radar considered for the project. It provides configurable settings and it has an application for the detection and tracking of objects.

It can be concluded that after consideration of the literature survey for rodent detection and individual survey for the senor models. The sensor listed below also fulfills the requirements stated for the project. Below is the table VII of the final hardware considered for the project

Device	Option1
PIR Sensor	HC-SR501
Ultrasonic	HC-SR04
Camera	Night vision IR-CUT
MMWaveRadar	IWR1642
CMWaveRadar	RadarIQ
Microphone	M500 USB

TABLE VII
FINAL LIST OF HARDWARE

VI. PROPOSED PROTOTYPE

A. *System Overview*

Based on the literature survey conducted above, the hardware and trap initial design is finalized for the project.

*1) **Hardware**:* As discussed above, the final hardware for the project is finalized

*2) **Trap Model**:* As discussed above, Sherman's design is considered for the Trap model design. Sherman trap design is modified for the requirements of the projects. The trap model consists of four parts separately.

- Cylindrical pipe for rodent entry and exit

The first component consists of two cylindrical pipes, that act as the mice's entrance and exit locations. The dimensions of the pipes are selected to allow the size of the rodents. To ensure all possibilities are covered, the cylinder diameter is selected to be 10-11 cm, to account for rodents with a maximum height of 9-10cm. The length of the cylinder is in the range of 30-40cm to accommodate rodents with a maximum length of 30cm.

- Bait Box

The next component in the design is the bait box. A three-way connector is utilized to secure the two cylindrical pipes on either side, with the vertical pipe held in place by the top of the connector. The connector dimensions are the same as those of the cylindrical pipes, while the bottom of the connector is designated for bait placement to attract rodents.

- Vertical Pipe

The Bait box is the third component in the design. The vertical pipe is held in place by the top of the three-way connection, which also secures the two cylindrical pipes on either side. The bottom of the connector is used to store bait to attract rodents. The diameter of the pipe ensures that the Raspberry Pi camera and microphone have unobstructed views

Below figure 7 is the design with the above-mentioned parts of the trap design

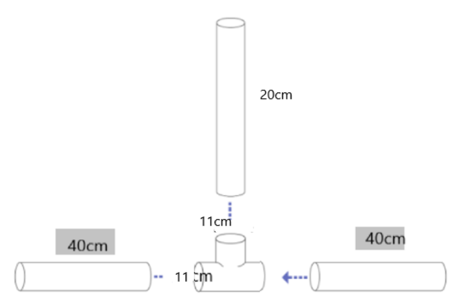


Fig. 7. Model

- Component Box

The fourth component of the design involves creating a box using a laser cutting procedure and transparent acrylic sheet material. This box serves as the storage space for the project's hardware and is placed on top of the vertical pipe. The box dimensions are determined by considering the dimensions of

all the hardware components to ensure a perfect fit.
Below is the table 8 with the dimensions of the hardware

Components	Length	width	Height	
Micrphone	113mm	40mm	10mm	Speaker 12mm
Camera	70mm	Very less	25mm	Circle 18mm 15mm
Raspberry pi(with casing)	95mm	65mm	29mm	
IWR1642	82mm	65mm		
RadarQ	55mm	55mm	10mm	
PIR	32mm	24mm	18mm	
Radar Stand(4)	82mm	65mm		Circle:6mm
Bread board	165mm	55mm		

Fig. 8. Component Dimension

- IWR1642 Radar: Within the component box, there are two small circular stands positioned at the bottom to support the IWR1642 radar stand. The radar is placed pointing outwards.
- RadarIQ: A rectangular hole has been created in the component box to place the radar at the bottom surface pointing outwards.
- Microphone: It should be held vertically at the bottom of the box, with the speaker pointing towards the bait box.
- Raspberry Pi Camera: The camera is located pointing downwards in the central portion of the box to provide maximum coverage of the connector
- PIR Sensor: The design incorporates a total of four PIR sensors, with one positioned to face downwards towards the bait. A square opening has been cut at the bottom of the component box to accommodate this sensor. Two PIR sensors are positioned to face the right and left sides of the box, with square openings cut on the respective sides of the box to hold them in place. The fourth PIR sensor is positioned to face the front side of the box.

Below figure 9 is the sketch for the placement of the components in the box

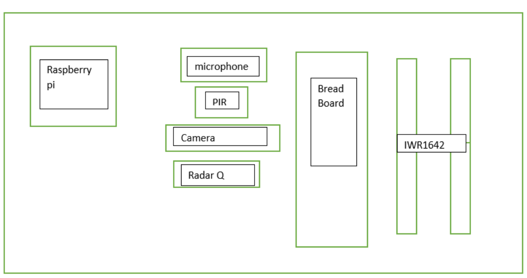


Fig. 9. Sketch For Box

- Trap Design

The below figure 10 is the complete trap model designed for the project

- Component box is additionally covered with plastic wrap to provide protection from moisture
- For stability additional pipe with weights is added to the design
- Additional box is used to store the power bank for the design

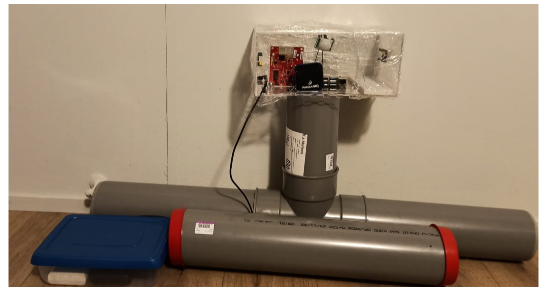


Fig. 10. Trap Model

B. *Software*

*1) **Functional Block**:* The main component of the prototype is the Raspberry PI model 4B 2 GB which functions as the processing core. The PIR sensor is connected to the raspberry pi with the breadboard. RadarIQ and IWR1642 radar is connected to the raspberry pi through a USB port. The microphone is also connected to the raspberry pi through the USB port. The camera is connected to the camera port in raspberry pi.// In the project, there are two main objectives that need to be achieved with the hardware. The placement of the hardware is decided based on the objective.

- Detection Of Rodents and Estimation of Population

The radar component is responsible for the precise detection and estimation of rodents in the area. PIR sensors are utilized to detect any rodent movement, which in turn activates the radar. Upon activation, the radar will monitor the designated area for five minutes, providing ample opportunity to detect any rodents present. Three PIR sensors are strategically positioned to cover all three sides of the trap, increasing the likelihood of detecting rodent movements and accurately capturing their presence.
Below figure 11 is the flow chart for the process explained above

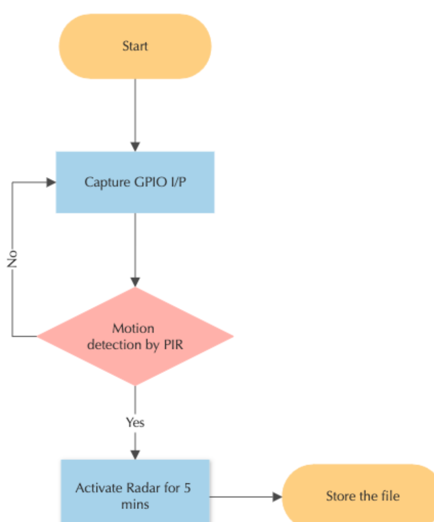


Fig. 11. First Flow Chart

- Capture Behaviour of the Rodents

To capture images and record the sound of the rodents, a camera and microphone are utilized. One PIR sensor is directed downwards towards the bait and is set to a high sensitivity level with re-trigger mode enabled. Upon detection of any rodent movement, the camera and microphone are activated. When motion is detected, the PIR sensor maintains a high output signal for a predetermined delay limit. If the motion is detected again within this delay window, the delay timer is reset to zero, enabling full motion capture of the rodents within the trap. Images are captured every second, with recordings saved at one-minute intervals.

Below figure 12 is the flow chart for the process explained above

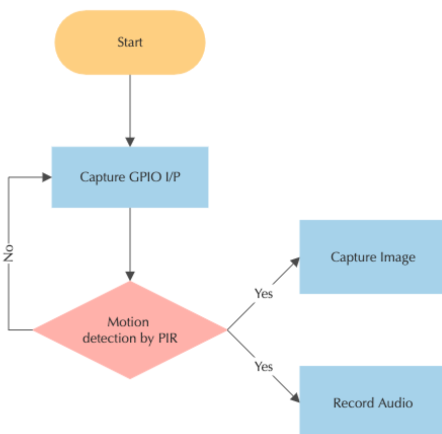


Fig. 12. Second Flow Chart

VII. Testing

A. Test Plan

The test plan is developed to facilitate the efficient testing of the components, with the aim of ensuring that all project requirements are met. In addition, the test scenarios are connected to the research question

1) Research Question 1: Detect and Estimate the population of rodents with a multi-sensor module
    - Detection of multiple objects
    - Detection with occlusion
    - Counting of multiple objects
    - Plot the point cloud object in the area
    - Detection with variation in velocity
    - Dimension information with point cloud semantics
2) Research Question2: how to achieve accurate and improved detection with modification in parameter and orientation
    - Detection with daylight and nightlight
    - Modify the radar configuration parameter
3) Research Question 3: How can rodent behavior be identified with multi-modal sensors

- How can camera data could be utilized for the rodent identification
- How can Radar point cloud data could be utilized for the rodent classification
- How can rodents' movement behavior be analyzed with radar

B. Performance Metrics

To validate the project's performance, testing individual components and functional block testing is considered. performance metrics are considered to verify the testing. Testing is performed with different testing scenarios and different situations. Multiple execution runs are performed for the testing.

The distance metric is considered for the radar to monitor the maximum distance measured. It is also useful to understand at what distance the radar measurement is reliable. Accuracy is important to get a detail on how many positive detections are observed. Error is used for the model testing of the rodents, to indicate that the correct class is detected. Error is also considered for missing the detection by radar. Precision is the relevant instance among all readings.

Metrics	Formula
Max Distance	Measured Distance
Accuracy	$\frac{TP+TN}{AllReadings}$
Mean Squared Error	$\frac{Error1+..+ErrorN}{N}$
Absolute Error	True Value- Measured Value
Precision	$\frac{TP}{FP+TP}$

TABLE VIII
Performance Metrics

C. PIR Sensor

To verify its performance during both daylight and nighttime, the PIR sensor underwent testing in a variety of settings. Each scenario was tested at least ten times to ensure accurate results. Separate tests were conducted to evaluate the PIR sensor's performance, allowing for a comprehensive assessment of its capabilities in each scenario. The potentiometer was fully rotated clockwise in order to test the PIR sensor at its maximum sensitivity. Potentiometer controls the delay by determining how long the output will stay HIGH after motion is detected. It can be altered between 1 second and around 3 minutes. The delay is adjusted by rotating the potentiometer; clockwise rotation lengthens the delay and anticlockwise rotation shortens it. Testing is performed at a distance of 1-meter to 5-meter range.

Below is the table IX with the testing results for the PIR sensor

During testing, it was observed that the performance of the PIR sensor varies depending on the level of daylight or nighttime conditions. Results indicated that the accuracy

Distance	Detection	Accuracy
1mm	yes	1
2mm	yes	0.95
3mm	yes	0.7
4mm	yes	0.4

TABLE IX
PIR-TEST-RESULTS

and range of detection were higher during daylight hours. Specifically, the PIR sensor was able to capture motion up to 4 meters away in daylight conditions. However, as the distance from the sensor increased, the number of successful detections decreased. Additionally, it was found that the performance of successful detections was reduced compared to the results obtained during nighttime testing scenarios. Based on these tests, it can be concluded that the PIR sensor is best suited for detecting motion within distances of 3 to 4 meters, taking into account external factors.

D. Camera

In order to verify its performance, the Raspberry Pi camera is utilized to capture images of rodents inside the trap. This test is conducted during both daylight and nighttime conditions. The captured images are saved every second with a file name format that includes the date and timestamp. This approach allows for the generation of a comprehensive dataset that can be used to classify rodents.
To conduct the test, the camera is installed in the components box and positioned facing downwards toward the bait area for rodents. When the PIR sensor, also facing downward toward the bait, detects the presence of rodents, the camera is activated. In order to simulate real testing conditions, artificial rodents are used in the test scenario.
To test the performance of the camera, multiple tests are performed. For the testing rodents are passed in the trap at a different speed. Collectively accuracy is calculated. When an image is captured with clarity it is considered true reading. If an image is not captured then it is considered a false reading. To also consider the effect of illumination, testing is performed both day and night time. Below is the images captured during the camera testing. Figure 13 is the testing result in the daylight. Figure 14 is the result captured in the night light.

- Image captured in daylight

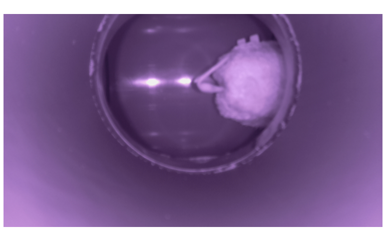


Fig. 13. Image Day Light

- Image captured at night light

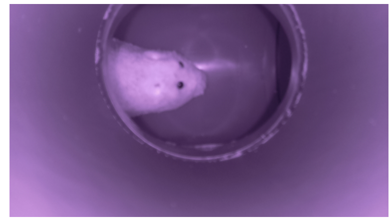


Fig. 14. Image Night Light

Illumination	Accuracy
Day Light	1
Night Light	0.95

TABLE X
CAMERA-TEST-RESULTS

E. Microphone

In this project, the microphone serves the purpose of recording ultrasonic range. To ensure the proper functioning of the microphone, an ultrasonic sensor is utilized. The ultrasonic sensor emits waves in the range detectable by the microphone, but not by humans due to their inaudibility. To visualize the recorded data, a graph is plotted. During the project setup, the microphone stores recordings for a duration of one minute, with the file name indicating the date and time.

F. IWR1642

Testing of the radar is divided into the test scenario mentioned above

*1) **Test Scenario: Detection of objects**:* To evaluate the resolution capabilities of the radar, it is positioned in a stationary location within an open, unobstructed area. A toy car is then manually moved between distances of 1m to 10m from the radar. The radar generates a point cloud which is plotted onto a 2D graph. The resulting visualization is captured using the Demo Visualiser tool provided by Texas Instruments. It helps to determine the detection and distance of the object in front of the radar. With the measured value absolute error is measured for the radar. It also helps to decide on the accuracy of the radar measurement.
Below figure 15 is the absolute error plot with the true distance on the X-axis and Error on the Y-axis

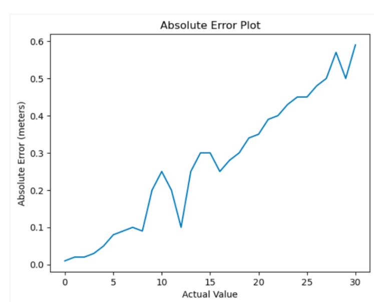


Fig. 15. Absolute Error Plot: Detection Of Objects

*2) **Test Scenario: Modify the radar configuration parameter**:*

- Radar Cross Section: refers to the measure of how much radar energy is reflected back toward the radar system by an object when it is illuminated by the radar's electromagnetic waves. In other words, RCS is a measure of the object's ability to reflect radar signals. The RCS of mice, being small animals with complex and irregular shapes, is generally expected to be relatively small compared to larger objects. Mice are made up of a combination of biological tissues fur, and other features. As a result, the RCS of mice can vary depending on the size, orientation, frequency of the radar system, and posture of the mice. The testing value of the RCS is set as 0.25 considerably small value.
- Range resolution in radar refers to the ability of a radar system to distinguish between two closely spaced objects along the radial direction (line of sight). It is determined by the duration of the transmitted radio frequency (RF) pulse. The radar system could distinguish between small objects in a range direction. Range resolution in a radar system can be influenced by other factors such as the system's signal-to-noise ratio, antenna characteristics, and processing techniques of the radar system. For the testing, detection with the best range is the objective. The value of the range resolution is defined in the demo visualizer tool as 0.244
- Unambiguous range in radar refers to the maximum range at which a radar system can accurately measure the distance to a target without encountering range ambiguities. Range ambiguities can occur in radar when multiple targets are located at different distances from the radar but appear to be at the same range due to the finite pulse width of the radar waveform. If targets beyond this range are present, their distances may be inaccurately measured due to the overlapping of radar returns from different ranges within a single radar pulse. In the testing, the value is defined as 5

The test Scenario Considered for the testing includes the detection of multiple objects. For the realistic testing of the scenario, different shapes of objects/rodents are included in the testing. Testing also includes the variation in the velocity of the object. This requirement is satisfied with the toy car.

Below figure 16 is the 2D plot with the toy car detected at the range of 8m

*G. **RadarIQ***

*1) **Modify Radar Parameter: Detection of object**:* To evaluate the resolution and detection range of the radar, it is placed in a stationary position within an open area. A toy car is used as the object of interest and is manually moved between distances of 1m to 10m from the radar. The radar generates a point cloud which is plotted onto a 2D graph. Python code is developed to facilitate the creation of the 2D graph. In order to observe changes in resolution at varying distances, a video is recorded while the object is moved from 1m to 10m. Additionally, the sensitivity of the radar is adjusted to test the difference in the point cloud. To ensure accurate object capture, the point cloud density is set to a high level. To include the variation in the testing scenario, different shapes of the objects and variations in the velocity are also included. Below mentioned XI table have the list of parameters that are modified for the testing

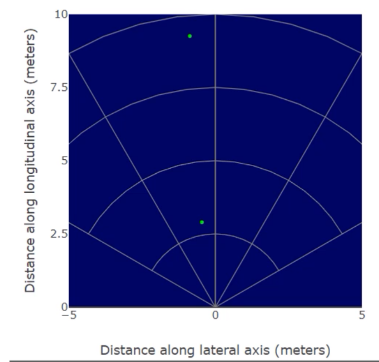


Fig. 16. IWRI642 Plot

Parameter	Value
Moving Filter	Moving and Stationary
Point Density	Very Dense
Sensitivity	Normal and High
Scene Calibration	TRUE
Capture Mode	Tracking and Point Cloud

TABLE XI
RADAR PARAMETER

- Scene Calibrate: is a property used to Calibrate the sensor to remove any near-field objects from the scene. This is useful to Remove the effects of an enclosure and hide static objects directly in front of the sensor. During the testing scene calibration is set to TRUE
- Moving_Filter: Is used to define the motion of the object. It includes the both moving and stationary motion of the object.
- Point_Density: Point cloud density is set to the dense density. It performs the aggregation of the points
- Capture_Mode: Two modes are defined for the radar. Point cloud mode is used for the plotting of the object. Tracking mode is used for counting the objects
- Sensitivity: Sensitivity alters the sensitivity of the radar. 0 is the Most sensitive. For the default sensitivity 5 is set. and 9 is the Least sensitive.

1) **When sensitivity is set to normal sensitivity**

- Point cloud has a y-axis that gives the information on the distance of the object from the sensor
- X-axis gives the information on the placement of the object to the right or left side of the sensor origin
- Point cloud is visible till 6m.
- Point cloud density is more concentrated and circular for toy car
- Point cloud accurately records the movement in the x direction till 6m

Below figure 17 is the 2D plot for the normal sensitivity and point cloud density set to Dense

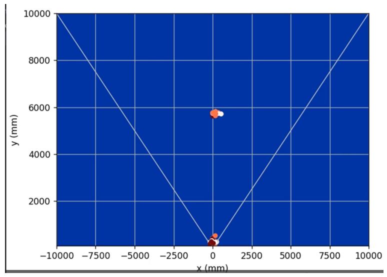


Fig. 17. 2D Plot

1) **When sensitivity is set to 2**

- Point cloud is accurate and visible till 8m
- Point cloud includes more points in the plot for the object

Below figure 18 is the 2D plot for the sensitivity set to 2 and point cloud density set to Dense The same set of tests is

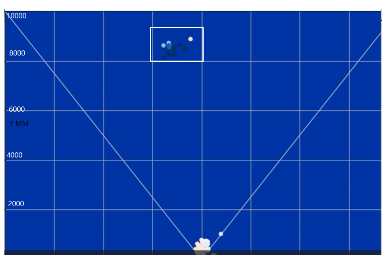


Fig. 18. 2D Plot2

performed and the 3D plot is captured for the scenario. For 3d graph generation, the RadarIQ controller is used.
Observations made with the 3D plot

- Point cloud in the X axis gives the information on the placement of the object to the right or left side of the sensor origin
- Y axis gives the information of the distance of the object from the sensor
- Z axis gives the dimension information of the object
- Point cloud does not include a background such as a wall in the plot
- Point cloud includes moving and stationary objects.
- Moving objects are reflected with higher intensity.

1) **When sensitivity is set to normal sensitivity**

- Point cloud is accurate and visible till 4 meters.
- Beyond, 4m distance point cloud is not visible.
- In the z-axis, the object lies between the midpoint of 0 to 500mm. It shows that object dimensions are between 0 to 250mm.

Below figure 19 is the 3D plot for the normal sensitivity and point cloud density set to Very Dense

1) **When sensitivity is set to 2**

- In this mode, there are more points in the plot for the object

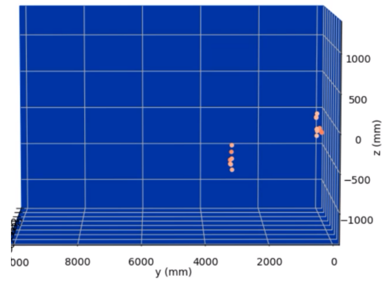


Fig. 19. 3D Plot1

- Point cloud is accurate and visible till 8 meters.
- In the z-axis, it is not possible to read the dimensions of the object because of the increased density of the points for the objects. The dimension of the object is not accurate

Below figure 20 is the 3D plot for the high sensitivity and point cloud density set to Very Dense.

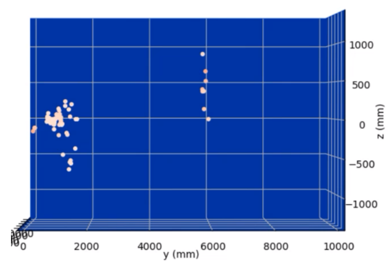


Fig. 20. 3D Plot2

With the data collected, accuracy for the two different modes of sensitivity is defined

Sensitivity	Distance	Accuracy
Normal	6m	1
Normal	7m	0.7
Normal	8m	0.5
High	8m	1
High	9m	0.7
High	10m	0.5

TABLE XII
POINT CLOUD ACCURACY

Below figure 21 is the plot with the accuracy defined for the distance

*2) **Point Cloud Semantics for object identification**:* Point cloud data is a type of digital representation of physical objects or environments. In RadarIQ, [38]point cloud data is obtained from a radar sensor and it is used to create a three-dimensional (3D) map of the surrounding environment. Point cloud data represent the location of the objects.

- X, Y, Z coordinates - The X, Y, and Z values are measured in meters or millimeters and it gives location information.
- X coordinates: It is the X plane and it gives the details for the placement of the object. It informs if the object is at the right or left side of radar

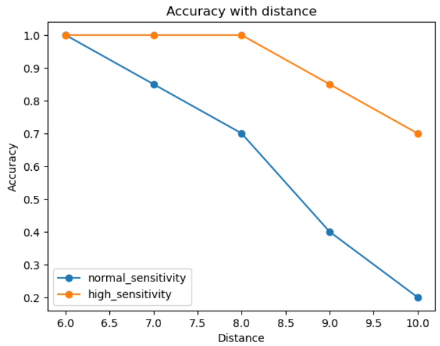


Fig. 21. Accuracy with Distance

- Y Coordinate: It represents the distance to the object
- Z Coordinate: It represents the height of the object
- Intensity - This value represents the strength of the returned radar signal at each point. The intensity can be used to estimate the reflectivity or roughness of the surface that the radar waves bounced
- velocity - This field indicates the velocity of the object.

To conduct the test, the radar is situated in a stationary position within an unobstructed area. An object is manually moved at distances ranging from 1m to 9m away from the radar. The test is conducted within a range of 1m to 9m in order to gain insight into how the point cloud semantics are influenced by distance. To understand how the point cloud gives the information for the object dimension.The dimension of the toy car is length 25cm(0.25m), Width 17cm(0.17m), and Height 14cm(0.14m).

1) **When an object is placed at 1m**

Observation

- In the point cloud with maximum and minimum X values the width of the object is identified. With the min and max values, it gives approx. width of the car that is 0.12m
- With the Y value, the position of the car is identified it gives approx. position of the car that is between 1.4 and 1.6
- With the Z value, it gives approx. height of the car is 6.4cm.[Tyres height]
- Points are correctly captured for the object at 1 to 1.5m

Property	Actual Value	Measured Value	Error
Width	0.17m	0.12m	0.05m
Height	0.1m	0.64m	0.36m
Position	1m	1m	0m

TABLE XIII
POINT CLOUD: 1M

1) **When an object is placed at 3m**

Observation

- With X value, approx. length of the car is 0.24m. It gives the error of 1
- With Z value, approx. height of the car is 0.19m. It gives an error of 5
- With Y value, object location is between 3.2m to 3.6m. It gives the error of .6
- With 1512 frames captured in the point cloud, 710 points are captured for the objects at 3.4 to 3.6m

1) **When an object is placed at a 5m distance**

Observation

- With X value, approx. length of the car is 0.22m. With actual value, it gives the error of 3
- With Z value approx. height of the car is 0.11m. With actual value, it gives an error of 6
- With Y value distance of the object is between 5.3m and 5.4m
- With 1016 frames captured in the point cloud, 219 points are captured for the objects at 5.3 to 5.4m

1) **When object at 7m**

Observation

- Out of 260 frames, 72 frames are captured for the object placed at 6.5 to 6.7m
- With X value, approx. length is 0.20m. With actual value, it gives an error of 5
- With Z value approx. height is 0.20m. With actual value, it gives the error of 3

Property	Actual Value	Measured Value	Error
Length	0.25m	0.20m	0.05m
Height	0.17m	0.20m	0.03m
Position	7m	3.5m	3.5m

TABLE XIV
POINT CLOUD: 7M

1) **When an object is kept at the 9m**

Observation

- With 824 frames captured in the point cloud, 134 points are captured for the objects at 8.9 m
- It is visible that less number of point clouds are captured for the object at 9m

Conclusion for Point Cloud Semantics Based on the test, it can be concluded that the radar's point cloud can identify the dimension of an object. However, as the distance between the radar and the object increases, the accuracy of the dimension and location identification decreases. This is due to fewer points being captured by the point cloud data as the distance increases. With the value measured above, it is possible to find the error in the object dimension.
Below figure 22 is the plot for the error observed in the height and length corresponding to the distance.

*3) **Distance**:* The purpose of this test is to determine the maximum detection range of the radar. The testing setup involves situating the radar at a fixed position within an open area. A toy car and rodents are used as objects and manually moved between distances of 1m to 10m from the radar. Using Python code, a measurement value for the object is calculated,

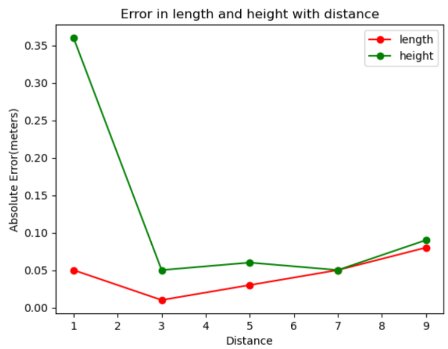


Fig. 22. Absolute Error for Dimension

which is considered the detected value in the subsequent table. The true value corresponds to the object's actual measurement. Below is the table XV with the detected value

True value	Detected Value	Error
1m	1m	0m
2m	2.1m	0.1m
3m	3.3m	0.3m
4m	4.35m	0.35m
5m	5.8m	0.8m
6m	7.2m	1.2m
7m	8.6m	1.6m

TABLE XV
DISTANCE TEST

Below figure 23 is the plot for the absolute error calculated with the distance

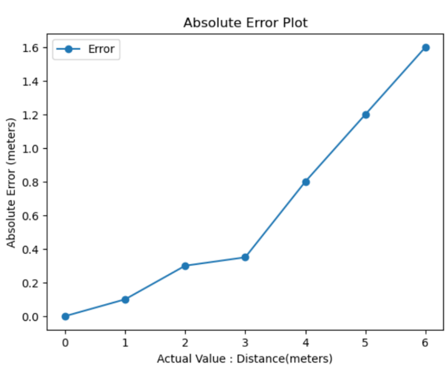


Fig. 23. Absolute Error for Distance

*4) **Velocity**:* This test is useful to understand that radar could perform detection accurately with velocity variation. With the Python code velocity of the object is calculated. To verify the real test scenario, toy cars, and rodent toys are used. The below table XVI is the testing results for the velocity

Object	Detected Value
Toy Car	5.6km/h
Slow Cycle	3.3km/h
Walk	2.6km/h

TABLE XVI
VELOCITY TEST

From the above table, it can be concluded that radar can detect the range of speed.

*5) **Detection and Counting of Multiple Objects**:* The purpose of this test is to verify the accurate detection and counting of multiple objects by the radar. The test involves utilizing the tracking mode of the RadarIQ sensor and using ten artificial rodents as objects. The testing scenario involves simulating the rodents crossing the field of view from either the left or right side of the sensor and exiting from the opposite side. To mimic a real-world scenario, multiple rodents are made to cross from both directions. Testing is conducted using different scenarios. The first scenario involves rodents crossing the radar boundary, entering from one side and exiting from the other. This scenario is designed to maximize the detection and counting of rodents, as it captures their complete movement. It also shows that in positive scenarios rodents are counted to a maximum range of 9 to 10m to the radar.

The second scenario is when rodents move in a straight line without crossing the radar boundary. This scenario is included as a negative test, as it is unlikely to occur frequently in real-time scenarios due to the random behavior of rodents in an open field. The radar boundary is narrow, and as rodents move near the radar, the chances of them not crossing the boundary are minimal.

The third scenario is when rodents enter from one side and exit from the same side, which results in detecting the rodents and recording them as "rodent detected" on the left boundary. However, there is a possibility of rodents not being included in the counting in this scenario Testing gives the TP when the rodent is counted in the scene. In the negative testing, the rodent is not counted. This case counts of the rodent is not included and it is considered a False reading. Below 24 figure is the plot with three scenarios outcomes

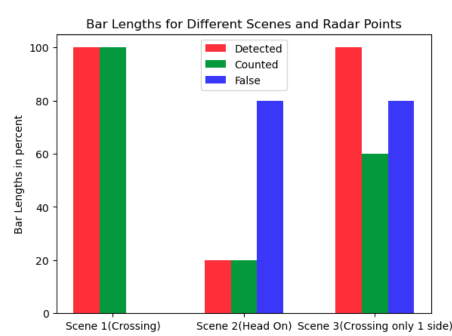


Fig. 24. Plot for Rodent Counting Test

*6) **Detection with Occlusion**:* To assess the radar's performance, an experiment is conducted with an object placed in front of it, with occlusion provided by a transparent sheet or plant. A transparent sheet is also used to cover the components box to protect the hardware from moisture. The test is performed twice, once without occlusion and once with occlusion. The goal is to validate if the radar can detect multiple objects with occlusion in place. The experiment results in the successful detection of various rodents even with occlusion. Point cloud formation is performed for the object at the 1m to 10m range, and it is observed that point cloud formation worked in the same way as without occlusion in front of the radar Below image 25 is the setup used for the occlusion testing

Fig. 25. Occlusion Setup

H. How can rodent behavior be identified with multi-modal sensors

*1) **Image Based Identification**:* For the analysis of the rodent, the initial approach is to utilize the images captured for the rodent inside the bait box. For greater accuracy of the model, the available data set is used. The data set includes the top view images of the rodents. As the project demands the faster detection of the rodents in the image, this means that model with a high defection rate, and inference rate is a good option. The YOLO model is a good option. For the training dataset of Ethological Evaluation of the Effects of Social Defeat Stress in Mice: Beyond the Social Interaction Ratio is used. Detection of the rodent class in the image is considered a True Positive. For negative testing images of the different classes of animals are included. Once the rodent is detected in the images, a bounding box is created with the details of the class
Below figure 26 is the Testing result for the true case

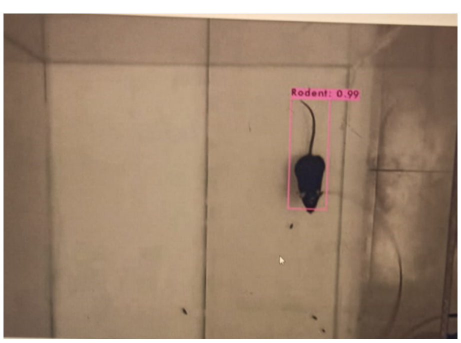


Fig. 26. YOLO-Test Result

Below figure 27 are the performance metrics for the prediction of the rodent class. It shows that map@50 for the rodent class mean average precision is 98.75%

```
 detections_count = 84, unique_truth_count = 80
class_id = 0, name = Rodent, ap = 98.75%        (TP = 79, FP = 1)

 for conf_thresh = 0.25, precision = 0.99, recall = 0.99, F1-score = 0.99
 for conf_thresh = 0.25, TP = 79, FP = 1, FN = 1, average IoU = 82.57 %

 IoU threshold = 50 %, used Area-Under-Curve for each unique Recall
 mean average precision (mAP@0.50) = 0.987500, or 98.75 %
Total Detection Time: 4 Seconds
```

Fig. 27. YOLO-MAP

*2) **Trajectory of Rodent**:* Radar point cloud semantics are employed to comprehend the behavior of rodents in an open area, allowing for tracking of their movements. The collected details are used for behavior analysis. For the testing movement of multiple artificial rodents is traced. The findings reveal the maximum distance covered by each rodent and enable the identification of groupings among them. Understanding the behavior of the rodents in the group and how they interact is a beneficial task in the actual testing setting. The graphic shows the movement of two mice in front of a trap, showing that one mouse stays close to the trap while the other mouse is moving away from it. This observation provides valuable insights into the behavior of rodents near food sources. Considering that rodents gather for food simultaneously, it raises the question of how their behavior might change in the presence of limited food availability.

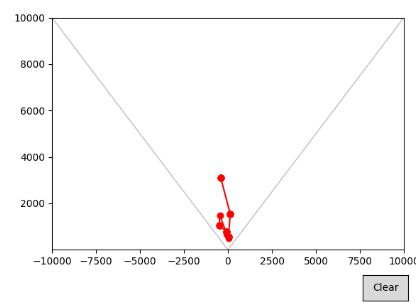


Fig. 28. Tracing of Rodent

*3) **Radar Data Classification of Rodents**:* For the classification of the rodents with the radar. Point cloud classification is used. It is a process in computer vision and remote sensing that involves categorizing points within a point cloud into different classes or categories based on their characteristics or attributes. with the 3D model of the rodents, the mesh is created and the model is trained for the rodents class. For the testing, the point cloud is created with the radar data captured for the rodents.

- Prepare the data: Convert the raw point cloud to a point cloud format that PointNet can recognize, such as the .ply or .obj format. For the dataset 3D model of a different kind of lab mouse is used.

- Pre-processing the data: This includes normalizing the point cloud data and splitting it into training and testing sets.
- Train the PointNet model on the training data.
- Evaluate the model: Evaluate the performance of the PointNet model on the testing data.
- Once the model is trained and evaluated, it can be used for prediction on new point cloud data.

Below figure 29 are the 3D models used for the training of the model For the testing, a 3D model of the rodent front facing is

Fig. 29. 3D Model

also used to increase the implementation of the model Below figure 30 is the 3D model of the front-facing rodent used for training the model

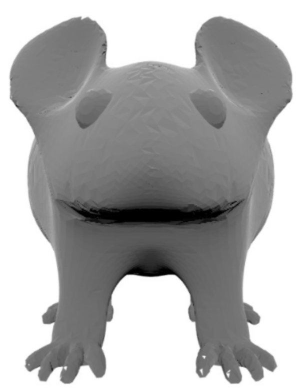


Fig. 30. Lab Mouse 3D Model

Predictions during the testing phase are derived from the training of the model. The testing phase involves two approaches: firstly, utilizing the mesh generated from the available 3D model, and secondly, generating the mesh from the radar point cloud. However, the results from the second testing approach are unsatisfactory due to inaccurate mesh generation as input to the model. Utilizing the alternative method for mesh generation with the point cloud can increase the accuracy. Below figure 31 are the testing results with the available 3D model. Lab_Mouse is the front-facing image of the rodent this is the reason it is different from the appearance of Black_Mouse. Based on the aforementioned findings, it can be inferred that radar point cloud data is valuable for object classification. Additionally, real-time radar processing that captures the mesh enhances the advantages of the model.

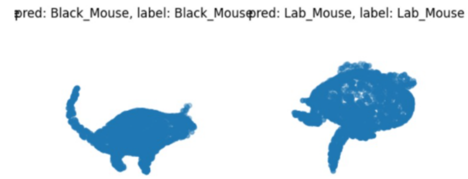


Fig. 31. Point Cloud Model:Test

I. Prototype Testing

During the testing phase, the prototype is deployed in an open field, allowing for testing with rodents in the surrounding area. The prototype is positioned at the university field with the bait placed inside the trap to attract animals. It is set up facing a tree, and the component box is protected with plastic wrap to prevent moisture damage. The Raspberry Pi is controlled using a VNC viewer. During the time the trap is installed outside, no rodents are detected by the trap. However, there are some birds in the vicinity that can be observed through visual inspection, as the camera is pointed toward the bait box and birds are reluctant to enter the trap. Thus, no images of birds are captured. In order to continue testing and generate meaningful results for the prototype, artificial rodents are used to create a realistic scenario. .Outcome of the testing scenario is divided into two parts for a better understanding of outcomes.

1. **Capture Behaviour of the Rodents**

The purpose of this test is to validate the individual functional block's performance. The first block comprises the PIR sensor, microphone, and camera. To test this setup, the hardware is mounted in the component box facing downwards toward the bait box, and an artificial rodent is placed inside the trap. Placement of the PIR sensor allows maximum coverage of the movement of the rodent in the bait box. The PIR sensor's sensitivity is set to the maximum for optimal functioning. The Re-trigger mode is activated so that the timer restarts every time the PIR sensor detects any movement. The PIR sensor detects the rodent inside the trap and triggers the camera and microphone. The camera takes pictures every second, and the microphone records audio for one minute. This testing is conducted in both daylight and nighttime conditions Below figure 32 is the image captured of a rodent in night light

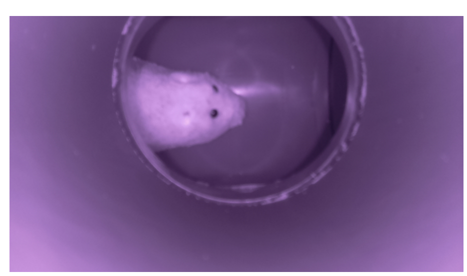
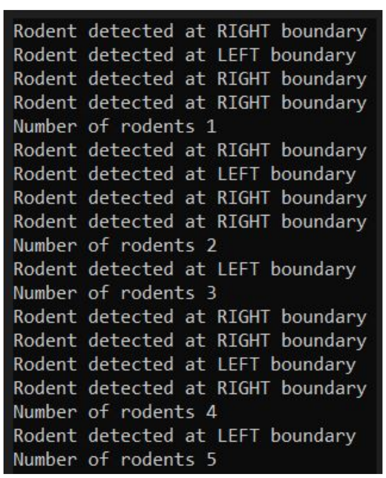


Fig. 32. Functional Block Testing1

2. **Detection Of Rodents and Estimation of Population** The second functional block consists of four PIR sensors and a radar. This test aims to validate the integration of PIR sensors with radar for the detection of rodents. Three PIR sensors are mounted to detect rodents within a 7m range. One PIR sensor is placed on the left side of the component box, another on the right side, and the third one in the middle of the left and right sides. The placement of the PIR sensors ensures the maximum coverage of the area around the trap. The PIR sensors are set to maximum sensitivity and Re-trigger mode. Whenever motion is detected by the PIR sensors, the radar is activated for detection. The radar remains active for 5 minutes to detect any rodents in the area, reducing power consumption. The PIR sensor covers an area of 5m around the trap. In case there are rodents in the nearby area not detected by the PIR sensors, the radar is activated every 10 minutes regardless of the PIR sensor readings. Artificial rodents are used to test the scenario, and they are moved within the radar's range from the left and right sides Test results show when motion is detected on the PIR sensor, it activates the radar. The radar starts capturing the point cloud and calculates the number of rodents crossing the radar range within 10m. When a rodent enters or exits on one of the boundaries of radar range, it is recorded as a 'left-enter', 'left-exit', 'right-enter', or 'right-exit'
Below is the outcome of the radar which indicated the estimation of the rodents population in the area. The below figure 33 is the output of the execution with ten rodent



```
Rodent detected at RIGHT boundary
Rodent detected at LEFT boundary
Rodent detected at RIGHT boundary
Rodent detected at RIGHT boundary
Number of rodents 1
Rodent detected at RIGHT boundary
Rodent detected at LEFT boundary
Rodent detected at RIGHT boundary
Rodent detected at RIGHT boundary
Number of rodents 2
Rodent detected at LEFT boundary
Number of rodents 3
Rodent detected at RIGHT boundary
Rodent detected at RIGHT boundary
Rodent detected at LEFT boundary
Rodent detected at RIGHT boundary
Number of rodents 4
Rodent detected at LEFT boundary
Number of rodents 5
```

Fig. 33. Multiple Object

IWRI642 radar is used to plot the multiple objects in the area, below figure 34 is the image with the output plot with three rodents captured in the plot.

3.**Validation**: Capture Behaviour of the Rodents:

- The output of the images captured with the camera is validated with the yolov4 algorithm. With the yolov4 it is concluded that a rodent is predicted in the image.
- The output of the point cloud data could be used for the identification and classification of rodents

Detection Of Rodents and Estimation of Population:

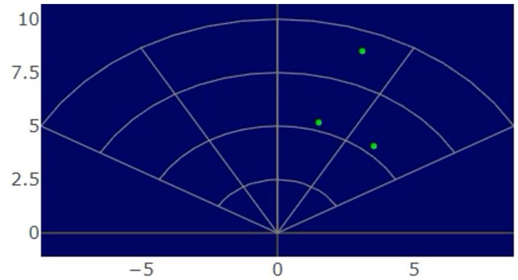


Fig. 34. IWR1642:Plot

- With the output of the RadarIQ sensor, counting captured with the radar is validated with the number of rodents used in the testing. That number of counted rodents is similar or near to the artificial rodent used in testing
- With the output of the IWR1642 radar, rodents are detected and it is visible in the plot. For validation, a number of rodents in the front of the radar is verified. That number of rodents is similar or near to the artificial rodent used in testing

J. Conclusion

The thesis presents a comprehensive investigation into the utilization of radar technology for rodent detection. The testing results reveal promising outcomes, demonstrating the radar's capability to plot multiple objects in the area and accurately count their detections. With the radar implementation in the project, it increases the accuracy of the detection and estimation of the population of rodents. The integration of a PIR sensor further enhances the system's functionality by enabling real-time monitoring of rodents' presence and triggering the camera and microphone accordingly. Moreover, the YOLO method is employed for effective analysis of the detected objects' class, adding a layer of sophistication to the system's capabilities. Another notable contribution of this research is the radar's ability to monitor object movement with varying velocities in front of the radar, even in the presence of occlusion. Radar point cloud classification is an important contribution to understanding the deep learning techniques for the radar dataset. It shows the working of the radar in detection and classification. It highlights the potential of radar technology for detection and tracking and applications in agriculture, pest control, and public health. The results of this thesis give future research and development in the field of rodent detection. It also facilitates a conclusion on the research questions with the findings of the project.

K. Future Work

Future work for the thesis could involve expanding the investigation of microphone recordings for rodent behavior analysis and collecting a larger dataset from diverse species and habitats. To utilize the findings of the camera and microphone together to understand the behavior of rodents. Incorporating image analysis techniques could provide a more comprehensive understanding of rodent behavior. This could include the identification of rodents based on age and sex. To identify the activity with the pose estimation. Validating and calibrating results against ground-truth observations and investigating the effects of various factors. Implementation in the real scenario with rodents also facilitates the dataset collection in real-time.

References

[1] “80-m Range Object Detection With IWR1642 mmWave Sensor Reference Design”. en. In: (2017), p. 13.

[2] Ian Agranat. “Detecting Bats with Ultrasonic Microphones”. en. In: (), p. 14.

[3] Shaashwat Agrawal. *Raspberry Pi Camera and its Variety*. en-US. Sept. 2020. URL: https://iot4beginners.com/raspberry-pi-camera-and-its-variety/ (visited on 11/30/2022).

[4] Fowzia Akhter et al. “IoT Enabled Intelligent Sensor Node for Smart City: Pedestrian Counting and Ambient Monitoring”. en. In: *Sensors* 19.15 (Jan. 2019). Number: 15 Publisher: Multidisciplinary Digital Publishing Institute, p. 3374. ISSN: 1424-8220. DOI: 10.3390/s19153374. URL: https://www.mdpi.com/1424-8220/19/15/3374 (visited on 11/14/2022).

[5] Nicola M. Anthony et al. “Comparative effectiveness of Longworth and Sherman live traps”. en. In: *Wildlife Society Bulletin* 33.3 (Sept. 2005), pp. 1018–1026. ISSN: 0091-7648, 1938-5463. DOI: 10.2193/0091-7648(2005)33[1018:CEOLAS]2.0.CO;2. URL: http://doi.wiley.com/10.2193/0091-7648(2005)33[1018:CEOLAS]2.0.CO;2 (visited on 11/22/2022).

[6] “Automated Parking Reference Design using 76-Ghz to 81-GHz AoP mmWave Sensor”. en. In: (2021), p. 16.

[7] Vikhram B et al. “Animal Detection System in Farm Areas”. en. In: *IJARCCE* 6.3 (Mar. 2017), pp. 587–591. ISSN: 22781021. DOI: 10.17148/IJARCCE.2017.63137. URL: http://ijarcce.com/upload/2017/march-17/IJARCCE%20137.pdf (visited on 11/14/2022).

[8] Vikhram B et al. “Animal Detection System in Farm Areas”. en. In: *IJARCCE* 6.3 (Mar. 2017), pp. 587–591. ISSN: 22781021. DOI: 10.17148/IJARCCE.2017.63137. URL: http://ijarcce.com/upload/2017/march-17/IJARCCE%20137.pdf (visited on 11/15/2022).

[9] Richard D. Beason, Rüdiger Riesch, and Julia Koricheva. “AURITA: an affordable, autonomous recording device for acoustic monitoring of audible and ultrasonic frequencies”. en. In: *Bioacoustics* 28.4 (July 2019), pp. 381–396. ISSN: 0952-4622, 2165-0586. DOI: 10.1080/09524622.2018.1463293. URL: https://www.tandfonline.com/doi/full/10.1080/09524622.2018.1463293 (visited on 11/16/2022).

[10] Ian Nicholas Best et al. “Farmers’ Knowledge, Attitudes, and Control Practices of Rodents in an Agricultural Area of Taiwan”. en. In: *Agronomy* 12.5 (May 2022). Number: 5 Publisher: Multidisciplinary Digital Publishing Institute, p. 1169. ISSN: 2073-4395. DOI: 10.3390/agronomy12051169. URL: https://www.mdpi.com/2073-4395/12/5/1169 (visited on 11/30/2022).

[11] Connor J Burgin et al. “How many species of mammals are there?” en. In: *Journal of Mammalogy* 99.1 (Feb. 2018), pp. 1–14. ISSN: 0022-2372, 1545-1542. DOI: 10.1093/jmammal/gyx147. URL: https://academic.oup.com/jmammal/article/99/1/1/4834091 (visited on 11/30/2022).

[12] Shivam Kumar Chauhan, Abhishek Sharma, and Avinash Kaur. “Animal Intrusion Detection and Prevention System”. en. In: *International Journal of Computer and Organization Trends* 11.2 (Apr. 2021), pp. 25–28. ISSN: 22492593. DOI: 10.14445/22492593/IJCOT-V11I2P308. URL: http://www.ijcotjournal.org/archive/ijcot-v11i2p308 (visited on 11/16/2022).

[13] Peter Christiansen et al. “Automated Detection and Recognition of Wildlife Using Thermal Cameras”. en. In: *Sensors* 14.8 (July 2014), pp. 13778–13793. ISSN: 1424-8220. DOI: 10.3390/s140813778. URL: http://www.mdpi.com/1424-8220/14/8/13778 (visited on 11/20/2022).

[14] *Communication rat*. en. URL: https://www.humane-endpoints.info/en/rat/senses-and-communication (visited on 11/26/2022).

[15] Thyagaraju Damarla, Asif Mehmood, and James Sabatier. “Detection of people and animals using non-imaging sensors”. In: *14th International Conference on Information Fusion*. July 2011, pp. 1–8.

[16] Mark Desholm. “Thermal Animal Detection System (TADS)”. en. In: (), p. 29.

[17] Alexandre Dore et al. “A Non-Invasive Millimetre-Wave Radar Sensor for Automated Behavioural Tracking in Precision Farming—Application to Sheep Husbandry”. en. In: *Sensors* 21.23 (Dec. 2021), p. 8140. ISSN: 1424-8220. DOI: 10.3390/s21238140. URL: https://www.mdpi.com/1424-8220/21/23/8140 (visited on 11/27/2022).

[18] Alexandre Dore et al. *A non-invasive radar system for automated behavioural tracking: application to sheep*. en. preprint. Animal Behavior and Cognition, Dec. 2020. DOI: 10.1101/2020.12.09.418038. URL: http://biorxiv.org/lookup/doi/10.1101/2020.12.09.418038 (visited on 11/27/2022).

[19] Muhammad Assaqafi Mohd Fisol and Warsuzarina Mat Jubadi. “Ultrasonic and infrared repelling device for controlling the population of rat in paddy field”. In: *2010 IEEE Asia Pacific Conference on Circuits and Systems*. Dec. 2010, pp. 359–361. DOI: 10.1109/APCCAS.2010.5774839.

[20] K.M. Gordon, Mark McKinstry, and S.H. Anderson. “Motorist response to a deer-sensing warning system”. In: *Wildlife Society Bulletin* 32 (June 2004), pp. 565–573.

[21] Jannis Gottwald et al. “BatRack: An open-source multi-sensor device for wildlife research”. en. In: *Methods in Ecology and Evolution* 12.10 (2021). _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/2041-210X.13672, pp. 1867–1874.

ISSN: 2041-210X. DOI: 10.1111/2041-210X.13672. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/2041-210X.13672 (visited on 11/18/2022).

[22] Dominique Henry et al. "Automated Monitoring of Livestock Behavior Using Frequency-Modulated Continuous-Wave Radars". In: *Progress In Electromagnetics Research M* 69 (June 2018). DOI: 10.2528/PIERM18040404.

[23] *How HC-SR501 PIR Sensor Works & How To Interface It With Arduino*. en-GB. July 2018. URL: https://lastminuteengineers.com/pir-sensor-arduino-tutorial/ (visited on 11/15/2022).

[24] Marcel P. Huijser et al. *The Reliability and Effectiveness of a Radar-Based Animal Detection System*. English. Tech. rep. FHWA-ID-17-247. Sept. 2017. URL: https://rosap.ntl.bts.gov/view/dot/34943 (visited on 11/20/2022).

[25] Nalini C. Iyer et al. "Millimeter-Wave AWR1642 RADAR for Obstacle Detection: Autonomous Vehicles". en. In: *Innovations in Electronics and Communication Engineering*. Ed. by H. S. Saini et al. Vol. 107. Series Title: Lecture Notes in Networks and Systems. Singapore: Springer Singapore, 2020, pp. 87–94. ISBN: 9789811531712 9789811531729. DOI: 10.1007/978-981-15-3172-9_10. URL: http://link.springer.com/10.1007/978-981-15-3172-9_10 (visited on 11/27/2022).

[26] Jhilam Jana et al. "Design and Development of Electronics Pest Repellent Using PIR Sensor and 8051 Micro-Controller". en. In: *Recent Advances in Intelligent Information Systems and Applied Mathematics*. Ed. by Oscar Castillo et al. Vol. 863. Series Title: Studies in Computational Intelligence. Cham: Springer International Publishing, 2020, pp. 758–766. ISBN: 978-3-030-34151-0 978-3-030-34152-7. DOI: 10.1007/978-3-030-34152-7_58. URL: http://link.springer.com/10.1007/978-3-030-34152-7_58 (visited on 11/14/2022).

[27] M. J. Keeling and C. A. Gilligan. "Metapopulation dynamics of bubonic plague". en. In: *Nature* 407.6806 (Oct. 2000). Number: 6806 Publisher: Nature Publishing Group, pp. 903–906. ISSN: 1476-4687. DOI: 10.1038/35038073. URL: https://www.nature.com/articles/35038073 (visited on 11/30/2022).

[28] Bridget A. Matikainen-Ankney et al. "Rodent Activity Detector (RAD), an Open Source Device for Measuring Activity in Rodent Home Cages". en. In: *eneuro* 6.4 (July 2019), ENEURO.0160–19.2019. ISSN: 2373-2822. DOI: 10.1523/ENEURO.0160-19.2019. URL: https://www.eneuro.org/lookup/doi/10.1523/ENEURO.0160-19.2019 (visited on 11/14/2022).

[29] Yoav Motro et al. "A comparison of trapping efficacy of 11 rodent traps in agriculture". In: *Mammal Research* 64 (Mar. 2019). DOI: 10.1007/s13364-019-00424-7.

[30] Abir Mukherjee et al. "ROADWAY MONITORING AND DRIVER WARNING SYSTEMS FOR WILDLIFE-VEHICLE COLLISION AVOIDANCE". en. In: (), p. 19.

[31] Mutinda Mutava Gabriel and Chuka University. "Arduino Uno, Ultrasonic Sensor HC-SR04 Motion Detector with Display of Distance in the LCD". en. In: *International Journal of Engineering Research and* V9.05 (May 2020), IJERTV9IS050677. ISSN: 2278-0181. DOI: 10.17577/IJERTV9IS050677. URL: https://www.ijert.org/arduino-uno-ultrasonic-sensor-hc-sr04-motion-detector-with-display-of-distance-in-the-lcd (visited on 11/16/2022).

[32] Irene Nandutu, Marcellin Atemkeng, and Patrice Okouma. "Intelligent Systems Using Sensors and/or Machine Learning to Mitigate Wildlife–Vehicle Collisions: A Review, Challenges, and New Perspectives". en. In: *Sensors* 22.7 (Mar. 2022), p. 2478. ISSN: 1424-8220. DOI: 10.3390/s22072478. URL: https://www.mdpi.com/1424-8220/22/7/2478 (visited on 11/19/2022).

[33] Yu Oishi et al. "Animal Detection Using Thermal Images and Its Required Observation Conditions". en. In: *Remote Sensing* 10.7 (July 2018), p. 1050. ISSN: 2072-4292. DOI: 10.3390/rs10071050. URL: http://www.mdpi.com/2072-4292/10/7/1050 (visited on 11/20/2022).

[34] K Shiva Prasad, A Hemanth Reddy, and M Ravi Kumar Goud. "Motion Activated Wild Life Capturing". en. In: (2017), p. 4.

[35] Anna Psaroulaki et al. "Rats as indicators of the presence and dispersal of six zoonotic microbial agents in Cyprus, an island ecosystem: a seroepidemiological study". eng. In: *Transactions of the Royal Society of Tropical Medicine and Hygiene* 104.11 (Nov. 2010), pp. 733–739. ISSN: 1878-3503. DOI: 10.1016/j.trstmh.2010.08.005.

[36] Abel van Raalte. "Animal activity recognition using a FMCW Millimeter Wave Radar". en. In: (), p. 5.

[37] Mohammad Hasan Rabiee et al. "Rodent-borne diseases and their public health importance in Iran". en. In: *PLOS Neglected Tropical Diseases* 12.4 (Apr. 2018). Publisher: Public Library of Science, e0006256. ISSN: 1935-2735. DOI: 10.1371/journal.pntd.0006256. URL: https://journals.plos.org/plosntds/article?id=10.1371/journal.pntd.0006256 (visited on 11/30/2022).

[38] *RadarIQ Manual*.

[39] S Santosh Kumar et al. "Sound Activated Wildlife Capturing". In: *2018 3rd IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT)*. May 2018, pp. 2250–2253. DOI: 10.1109/RTEICT42901.2018.9012357.

[40] V. Shapoval et al. "Application of Doppler Radar for Wildlife Detection in Vegetation". en. In: *Scientia Agriculturae Bohemica* 49.2 (June 2018), pp. 136–141. ISSN: 1805-9430, 1211-3174. DOI: 10.2478/sab-2018-0019. URL: https://www.sciendo.com/article/10.2478/sab-2018-0019 (visited on 11/20/2022).

[41] Yegor Sinelnikov et al. “Mice ultrasonic detection and localization in laboratory environment”. en. In: Jacksonville, Florida, 2016, p. 010005. DOI: 10.1121/2.0000170. URL: http://asa.scitation.org/doi/abs/10.1121/2.0000170 (visited on 11/17/2022).
[42] Kim Arild Steen et al. “Automatic Detection of Animals in Mowing Operations Using Thermal Cameras”. en. In: *Sensors* 12.6 (June 2012), pp. 7587–7597. ISSN: 1424-8220. DOI: 10.3390/s120607587. URL: http://www.mdpi.com/1424-8220/12/6/7587 (visited on 11/20/2022).
[43] Mrs E Suganya et al. “Surveillance Robot for Unauthorized Areas Using Arduino and Location Mapping”. en. In: 8.2 (2018), p. 4.
[44] Mark Tobin and Michael W. Fall. “Pest control: rodents”. In: *Pest Control: Rodents* Encyclopedia of Life Support Systems (EOLSS) (Jan. 2005).
[45] Franck Trolliet et al. “Use of camera traps for wildlife studies. A review”. In: *Biology Agriculture Science Environnement* 18 (Jan. 2014), pp. 446–454.
[46] Ioana Udrea et al. “New research on People Counting and Human Detection”. In: *2021 13th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)*. July 2021, pp. 1–6. DOI: 10.1109/ECAI52376.2021.9515115.
[47] Colin Webster and Robert MacDonald. “Predicting Criminality? Risk Factors, Neighbourhood Influence and Desistance”. In: *Youth Justice* 6 (Apr. 2006), pp. 7–22. DOI: 10.1177/1473225406063449.
[48] Robin C. Whytock and James Christie. “Solo: an open source, customizable and inexpensive audio recorder for bioacoustic research”. en. In: *Methods in Ecology and Evolution* 8.3 (2017). _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/2041-210X.12678, pp. 308–312. ISSN: 2041-210X. DOI: 10.1111/2041-210X.12678. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/2041-210X.12678 (visited on 11/21/2022).
[49] Gary Witmer. “Rodents in Agriculture: A Broad Perspective”. In: *Agronomy* 12 (June 2022), p. 1458. DOI: 10.3390/agronomy12061458.
[50] Yusman, Aidi Finawan, and Rusli. “Design of Wild Animal Detection and Rescue System with Passive Infrared and Ultrasonic Sensor based Microcontroller”. In: *Proceedings of MICoMS 2017*. Vol. 1. Emerald Reach Proceedings Series. Emerald Publishing Limited, Jan. 2018, pp. 415–422. ISBN: 978-1-78756-793-1. DOI: 10.1108/978-1-78756-793-1-00042. URL: https://doi.org/10.1108/978-1-78756-793-1-00042 (visited on 11/14/2022).
[51] Yusman, Aidi Finawan, and Rusli. “Design of Wild Animal Detection and Rescue System with Passive Infrared and Ultrasonic Sensor based Microcontroller”. In: *Proceedings of MICoMS 2017*. Vol. 1. Emerald Reach Proceedings Series. Emerald Publishing Limited, Jan. 2018, pp. 415–422. ISBN: 978-1-78756-793-1. DOI: 10.1108/978-1-78756-793-1-00042. URL: https://doi.org/10.1108/978-1-78756-793-1-00042 (visited on 11/15/2022).
[52] Sarah M. Zala et al. “Automatic mouse ultrasound detector (A-MUD): A new tool for processing rodent vocalizations”. In: *PLoS ONE* 12.7 (July 2017), e0181200. ISSN: 1932-6203. DOI: 10.1371/journal.pone.0181200. URL: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5519055/ (visited on 11/19/2022).
[53] Zhaonian Zhang et al. “Acoustic Micro-Doppler Gait Signatures of Humans and Animals”. In: *2007 41st Annual Conference on Information Sciences and Systems*. Mar. 2007, pp. 627–630. DOI: 10.1109/CISS.2007.4298383.

VIII. Appendix

A. PIR Sensor

As per the details in the article [23] A pyroelectric sensor and Fresnel lens make up the sensor. There are two distinct infrared sensor electrodes, one giving the positive output and the other the negative output, which make up a pyroelectric sensor. The initial halves experience a positive differential change when a warm body intercepts them. The other half of the sensor generates a negative differential change. Motion is discovered by interpreting this voltage change. The PIR sensor's range and field of vision are expanded by the Fresnel lens. PIR sensor is also used for the pedestrian detection algorithm. Research by [4] utilized the Field of view of the six PIR sensors to detect and monitor the movement of the pedestrian. PIR sensors pick up on movement and give the information into a count of pedestrians and a direction of travel. The developed system is put to the test throughout the day. This technology has a 95% accuracy rate when counting pedestrians while excluding any movement of domestic animals. This project encourages locating problem areas and taking the appropriate steps to increase pedestrian security and enhance facility conditions. Businesses can manage resources more effectively and keep an eye on the flow of foot traffic

B. Ultrasonic Sensor

The transmitter, which uses piezoelectric crystals to generate sound, and the receiver, which picks up the sound after it has traveled to and from the target, are the two primary parts of an ultrasonic sensor. A transmitter drum that transmits ultrasound and a receiver drum that receives ultrasound that is reflected from an object make up the sensor. Raspberry Pi or an Arduino works with sensors. The module sets the echo Pin to high as soon as the ultrasound is released through the emitter. Transmitted ultrasound moves ahead until it encounters an object, at which point it reverses direction. The receiver picks up the ultrasound that was reflected. Echo Pin becomes low upon receipt of the reflected ultrasound by the receiver. Now, the time it takes for the ultrasound to travel from the source to the item and back is equal to the amount of time the echo Pin was high.

The ultrasonic sensor is used for object detection and estimating the position. The below research used the sensor for the navigation of the robot. The paper by Suganya[43] focuses on the detection of objects and estimation of the distance. HCSR04 Sensor emits ultrasonic waves of 40Khz frequency at a distance of 2cm to 400cm. Whenever any obstacle is present, the waves would be reflected back from the object. This benefits the application of the detection of obstacles in unknown and dangerous spaces. With the test, it was discovered that the ultrasonic operation's minimum and maximum ranges were 5 cm and 250 cm, respectively. The trial was carried out outside, and the robot recognize the obstacle's presence.

Another application for the ultrasonic sensor is people counting and human detection. In the paper by Udrea, Alionte [46] Ultrasonic sensor is used to determine the number of people. It includes people detection and the number of people in the room. Identification of the people in the gathering place is helpful to provide safety measures. In the research one setup is done with PIR sensors and the second setup is done with two ultrasonic sensors. It uses HC-SRO4 and HCSR05 sensors and the measurement is 50% correct in detection.

The primary goal of this work [15]is to create algorithms for people detection utilizing several sensor modalities. A single person walking, two people walking, multiple people walking, one person leading an animal, two people leading an animal, and three people leading an animal are a few of the scenarios employed for data gathering. There are 26 scenarios in all, in various combinations. The information is gathered over the course of four days.

In the study by Mutinda and University [31]the use of acoustic and ultrasonic sensors for the detection of people and animals. Ultrasonic data is rich in information and signature of humans and animals. It utilized ultrasonic data to count the number of people. Ultrasonic information is utilized for classification and to determine how many targets are there. It is possible to classify objects with a high percentage of accuracy using all three sensors in design.

The Arduino Uno and the HC-SR04 ultrasonic sensor were used as part of the hardware. According to the study, the sensor may be used to display distance values on the LCD and properly estimate the position of an approaching object. As a result, this technique for detecting and measuring distances is effective and ensures accurate measurements of small distances up to 150 cm. This distance sensing and measurement device has a wide range of uses, such as in traffic and industrial settings where proximity detection is necessary.

The main concept of the project [34], is to control the movement of the camera based on the ultrasonic sensor. Ultrasonic sensor HC-SR04 is used to detect the animal in the range. A sensor works by emitting waves at a target object, then using a detector to catch the waves that are reflected back. then uses a detector to catch the waves that are reflected off the item. The Sensor uses the gathered data to establish whether an object is there or to calculate its distance from it. With this kind of sensor, the distance between the sensor and an object is calculated using the speed of sound and the amount of time it takes for ultrasonic waves to travel from the sensor to the object.

C. Radar

Radio waves are transmitted from a radar transmitter, which then reflects back from the object to a radar receiver. Radar can provide information about the location, movement, and other characteristics of objects by measuring the time delay and frequency shift of the returned signals. Radar is widely used in various fields, such as aviation, navigation, meteorology, military, and monitoring and tracking objects or phenomena of interest

Paper [17] used a millimeter-wave FMCW radar system for tracking the animal. The experiment is performed on 58 lambs in July 2019 at the French National Research Institute for Agriculture, Food, and Environment (INRAE). Detection is performed in both indoor and outdoor environments. For indoor, sheep were introduced in the area(2m*7m).For the outdoor, sheep in the corridor(10*60m). Data is collected with a video camera, infrared sensors, and radar. In the FMCW radar MIMO-77-TX4RX8, the signal is backscattered by the sheep. Within a 45 m range, radar tracks the 2D trajectories of walking animals that are untagged. It produces fewer false detection rates and needs 10 times less processing time.

In the paper by Alexandre Dore, Cristian Pasquaretta [18] also utilized the millimeter-wave FMCW radar MC33MR2001R for tracking the animal. It used a radar tracking device to examine the 2D animal motions in a 45m range. High-resolution 2D radar trajectory data allows the identification of novel animal behavioral patterns.

Research on activity recognition and monitoring behavior in humans and animals has the potential to reveal information about the health of both their bodies and minds. Behavioral selection is becoming more crucial in animal production. To describe animal response and look into genetic determinism, a variety of behavioral traits—including motion—are experimentally recorded. In the study by [22] uses a 24 GHz FM-CW (DK-sR-1030e model from IMST GmbH) radar to automate the monitoring of sheep behavior. Microwave FM-CW radars have good short-range performance (100 meters) and good spatial resolution (10 cm). To compare the positions given by the radar with the animal's actual location, a camera (400 x 320 pixels) was set up adjacent to the antennas. The results display the animal's sequential ranges up to 12 meters.

In the paper by [53] the gait signatures of people and four-legged animals are recorded using a micro-Doppler active acoustic sensor device both indoors (in a 30-foot-long corridor) and outdoors (farm). The head, chest, and limbs of a walking human (or animal) reflect the acoustic wave that the transmitter (Tx) emits. Another ultrasonic transducer (Rx) receives the reflected signal, which is subsequently amplified using a variable gain chain and digitalized. Ten seconds of data are taken for each trial while the dog, horse, or person walked toward or away from the transducers.

D. Microphone

The research in the paper [39] is aimed to capture the animal using the ultrasonic microphone and camera. It consists of a radio transmitter that continuously generates radio waves; when an animal makes noise, the surface of the plane is influenced, which causes fluctuations in the radio wave. The microphone picks up this wave and hears the sound. As the heard sound is analyzed, the camera is activated and aimed in the direction of the sound source

The automated system makes use of microphones. The project's [39]main guiding principle is to take images of animals. The main concept of the project is autonomous web camera control using an ultrasonic sensor and a microphone. When the sound value exceeds a threshold point, the camera will turn on based on the recognition of animal sound. A specific range of animal sounds will be picked up by the microphone. If there are no animals within the required range, the web camera installed in the forest won't record anything.

E. Thermal Camera

There are important characteristics that need to be considered for a trap. First is the trigger speed, Trigger speed is the amount of time the camera must wait before taking a photo after an animal enters its detection range and blocks the infrared beam. In the case of swiftly moving animals, a very responsive camera (with a quick trigger speed) would be required so it could capture images of the recognized animal before it vanished from view. If the trigger speed is too sluggish, the camera might only capture a portion of the animal or take empty photographs. When a camera is placed in front of the bait, animals that come to eat it stay longer. Garrote et al., 2012; Trolle et al., 2003) even when the camera has low responsiveness (large time delay). Using bait makes it possible to identify animals more accurately.

The field of view is the second feature. The area that the camera lens captures and that may be seen in photos is known as the field of view. The advantage of having a wider detection zone than the field of vision is that it makes it easier to photograph moving animals. The restriction is to only snap photos of nothing. The advantage is well-centered images when the detection zone is smaller than the field of vision. This can be very helpful in identifying huge creatures.

The resolution should be large to capture the image with clarity. For monitoring wildlife activities at night, night vision is thought to be useful.

Recovery time is the length of time required for the camera to get ready to take the next picture after the previous one has been recorded is known as the recovery time. When wanting to capture a whole sequence of a behavior, a camera that can snap several photographs in quick succession might be quite helpful. Slow recovery time is not an issue while monitoring diversity.

[13] also helps to identify and detect wildlife in agricultural fields. The research described in this paper helps thermal imaging software automatically identify and categorize animals. In the experiment, the top-view photographs are used as the basis of the procedures and outcomes. With a classification accuracy of 84.8%, the proposed feature extraction and classification

scheme exhibits good detection and classification performance for recording heights under 10 m. The performance declines to an accuracy of 75.2% in the altitude range of 10–20 m. Above 20-22m performance is reduced.