The estimation of rodent population in an area with the use of IR&RGB camera images and USV sounds.

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Fig. 1. Rodents in natural habitat, 2020

Every year billions of dollars of damage are being dealt to agriculture and houses by rodents, which results in rodents being classified as the biggest animal pest in the world. Rodents tend to not only affect agriculture by eating and spoiling large amounts of food they also affect water supplies and disease spread. Over thirty-five diseases can be transmitted by rodents including for example severe diseases like plague and Salmonella. Taking all these facts into account, it is obvious that the rodent population should be monitored and if necessary controlled. In order to control the population rodenticides need to be evaluated which can be done once a monitoring device has been established. This research explores the possibility of creating an energy-efficient monitoring device which can identify rodents in a certain area with the use of sensors. The sensors entail a combination of an IR camera, an ultrasonic sensor and an PIR sensor. Some of the main findings are that the camera provides excellent range in darkness and provides high quality images. The ultrasonic and PIR sensor provide good quality till 3 meters which can be used to trigger data capturing. In order to extend the range further calibration can be done or new technologies can be used such as Radar. Radar proved to be a high quality option up to at least 10 meters.

Additional Key Words and Phrases: Rodents, population, PiCamera, IR sensor, USV sensor, PIR sensor, HC-SR04, HC-SR501, MMwave, DHT22, IWR1642BOOST, Detection, Radar

1 INTRODUCTION

Rodents are mammals which can be characterized by continuously growing incisors in the upper and lower jaws. Well-known rodents species entail squirrels, mice, rats, beavers, guinea pigs and hamsters. Most of those species have been around for more than 30 million years. Even though these species have been around for such a long time, mankind has not been able to control these animals. Rodents are considered one of the biggest pests in the world. The main reason for that is that rodents affect the food security of communities and cause high value losses in crop yield. In Ethiopia the damage of rodents on the barley yield was estimated to be 22kg per hectare which equals 121.9 US dollars.[17]By controlling rodents, large increases in income and yield can be seen as studies have shown in Asia where the estimated increase of income was over 15%. [15]

These animals affect not only the food security of communities but also the water supply and disease spread. Rodents are known to spread endemic flea which is a key plague vector. [14]. Another example is the spread of the Leptospirosis virus of which rodents are the major cause of in India. By controlling the rodent population the government achieved a total reduction of 61% virus prevalence in the area. [1] The rodent population in certain areas can grow quickly and exponentially based on the conditions in the area. An example of this was recorded in Myanmar where nearly 2.9 million rats were estimated to be in the area due to a recent cyclone.[10]. For this reason it is important for municipalities and farmers to be able to monitor the population in the area in order to prevent outbreaks of diseases or a shortage in water supply.

All of this shows that rodents should be monitored and dealt with accordingly. Many calls have been made towards rodent behaviour analysis and with this improve the control of population numbers. The goal of this research is to lay the foundation for future research of rodent population and rodent behaviour. More specifically the rodent population in Cyprus since this is one of the countries with a high population of rodents. The main issue in this country is that rodents affect the roots of trees which cause them to die over time. This will be achieved by creating a smart sensor trap which is able to record and identify the rodents in Cyprus. The sensors that will be used are an IR&RGB camera, PIR sensor and an USV sensor. An IR&RGB camera stands for infrared and RGB camera which is able to take pictures in daylight and in night time with the use of infrared technology. A PIR sensor stands for passive infrared sensor and can

TScIT 37, July 8, 2022, Enschede, The Netherlands

detect movement of animals by using infrared technology. The last sensor is the USV sensor which stands for ultrasonic vocalization and is able to record ultrasonic sounds which can not be detected by the human ear. The smart trap should not only record the amount of rodents but should also record images and USV sound which can be used to determine the behaviour of the rodents as well.

2 PROBLEM STATEMENT

Despite the fact that there has been some research done already in the field of detecting animals using technology such as IR and USV sensors, the application on rodents specifically is relatively new. Also there is some urgency bound with this research since rodents are becoming more of a problem in Cyprus. Populations are increasing and the damage done by these rodents is noteworthy. In order to solve this problem the behaviour and the population of the rodents must be observed. This research will analyze and explore new technologies and designs in the field of rodent detection. In addition it will attempt to observe the behaviour of the rodents in the specified area. After finishing the design and creating the product it will validate the outcomes and check whether the initial goal has been accomplished.

2.1 Research Question

From the problem statement, the following research question can be made. "To what extent can we monitor the behaviour of rodents in different environments using modern sensor technologies?"

2.2 Research subquestions

The research question can be answered by solving the following subquestions:

(1) How can we integrate an IR&RGB camera, ultrasonic sensor and a PIR sensor in order to identify rodents in an area?
(2) How effectively can rodents be detected by means of IR, PIR and ultrasonic sensors?

3 RELATED WORK

In order to find relevant work an initial literature search was conducted through Scopus and Google scholar. The main search terms used were “IR&RGB”, “Rodents”, “Population”, “PIR” and “USV” to identify the basic concepts and explore what already exists.

Regarding the sensor technology the first sensor that will be discussed is the PIR sensor. In their 2017 paper Cambra [4] presents a wireless sensor network where with the use of multiple low cost nodes rodents can be identified with an accuracy of 92-93% using only the PIR sensor as a measuring tool. Later in 2019 Matikainen-Ankney [11]further developed such a concept by building an in-cage device with a PIR sensor to detect not only the presence of rodents but also their activity type and duration which is called RAD, rodent activity detector.

The most important sensor in this research will be the USV sensor. In 1979 Smith, J. C. [16] showed that the sound mice transmit varies in different environments. Later in 2012 research showed that the USVs produced by mice represent their state, for example this could be arousal and that it differs for females, males and pups (newborns)[13]. For that reason identifying mice by their sound has proven to be a technically difficult challenge, but in 2017 they developed a tool called “Automatic mouse ultrasound detector” (A-mud) which solves the problem partially.[18] In 2022 Goussha Y. et al [8] presented a new neural network for capturing USVs out of recordings which is shown to be difficult since the sounds produced often have an extremely short duration and are not hearable by humans.

In this research not only the PIR sensor will be used but also an IR&RGB camera. On this topic there is little research done regarding rodent detection with IR&RGB cameras and neural networks. However since these cameras use heat as a detection method, other research oriented on detection of warm-blooded animals or humans can be useful as well. In 2022 Ding, I.-J., & Zheng, N.-W [5]presented a method of detecting hand gestures using RGB&IR image data and neural networks.

The combination of all sensors have been opted to be used in applications. One example was created in 2016 where researchers opted to use a combination of these sensors to implement a security solution for agriculture[3]. It worked quite simple, once the PIR sensor detected a mouse it recorded video and an USV between 40-65 kHz was produced which worked aversive for mice. However this solution had problems with accurately detecting mice and verifying the results. In addition USV can have a positive effect on plant growth which can be useful when implementing solutions in agriculture. [2]

4 METHODOLOGY

In order to answer the research question there are several steps that need to be taken. First of all, all relevant sensors and technology used will be explained. When this phase is complete the aim is to create a prototype combining all the sensors which is able to integrate and process the data. Finally the individual sensors need to be evaluated to check whether they live up to their proposed performance. Once this is done the prototype itself can be evaluated and tested.

Firstly all sensors and components used will be discussed in combination with their theoretical specifications. Then the prototype will be discussed and show how the individual sensors are combined. Then will be discussed what software is used in order to get the prototype and individual sensors running. Lastly the methodology used to test and verify the performance of the prototype and sensors individually will be discussed.

4.1 Sensors

First of all we will discuss what sensors and components have been chosen and what their specifications are.

Radar sensor. The IWR1642 Boost sensor is a high-quality radar sensor which operates in the 76 to 81GHz band to detect moving objects. It is able to measure range, velocity and angle of the objects. In addition it is able to detect targets within a range of 200 meters. The limited field of view of 120 degrees is the only drawback to the sensor. However this drawback is not a problem for this project since it is only required to capture rodents in front of the radar sensor. The sensor can be connected through an USB-A - Micro-USB cable with any device running an operating system. The high price

Table 1. Sensor specifications.

Sensor	Model	Current	Voltage	Fov	Range	Price
PIR sensor	HC-SR501	65 mA	5 V	120	7 M	€2.50
Microphone	SPU0410LR5HQB	5 mA	1.5 - 3.6 V	unknown	unknown	€1
IR Camera	WS-10299	200-250 mA	3.3 V	75.7	8 M	€27
Ultrasonic distance sensor	HC-SR04	15 mA	5 V	15	4 M	€3
Temp sensor	DHT22	2.5 mA	3.3 V	-	-	€8
Radar	IWR1642	2.5A	5 V	120	200 M	€400
Powerbank	Charmast 23800mAh	-	-	-	-	€45

of around 400 euros makes it that the sensor will not be included in the prototype but will be evaluated to check its performance.

Ultrasonic distance sensor. The HC-SR04 sensor is build up from two ultrasonic transmitters, a receiver and a control circuit. The sensor measures the distance between the sensor and the object by sending out ultrasonic sound pulses of 40 KHz and calculating the time it takes to read the pulse on the receiver. The distance is calculated by the time difference multiplied by the speed of the sound pulse and divided by two since the pulse goes back and forward. The sensor has four pins and requires 5V through the VCC pin and a ground connection through GND pin.[6] The sensor sends out eight ultrasonic sound pulses when the TRIG pin receives a high signal of at least 10 nanoseconds from the device. The ECHO pin then generates a high signal once the reflection of the pulse is received.

PIR sensor. The HC-SR501 sensor is a passive infrared sensor which is able to detect movement. The sensor has a sensing range of 120 degrees with a maximum distance of 7 meters.[12] The sensor has three pins and requires a 5V VCC connection and a connection to ground through the GND pin. The sensor receives a high signal through the middle pin once movement or other infrared radiation emission changes in the field of view of the sensor has been detected. The sensor has two potentiometers through which the sensitivity and the time that the sensor locks on the high signal can be adjusted. The sensor also has a jumper which allows the sensor to be set to repeatable and non-repeatable mode. Repeatable mode entails that the sensors transmits a high signal as long as movement is detected. Non-repeatable mode entails that the sensor transmits a high signal once movement is detected for the lock time which can be adjusted with the potentiometer.

PiCamera. The WS-10299 camera sensor is able to record and capture images during daytime and nighttime. The camera uses two mountable infrared LED boards to illuminate the field of view at night with infrared light. The camera captures footage at 1080p and has a 75.7 degrees viewing angle and uses the same OV5647 sensor as the original Raspberry PI camera. The OV567 sensor has a resolution of 5 megapixel which should allow for sharp pictures to at least 3-5 meters. The price of the sensor of only 27 euros also makes it a great option for this project.

Microphone. The microphone SPU0410LR5HQB that was ordered was chosen for its performance in the ultrasonic audio recording performance. In addition this microphone is widely adopted in bat detection communities which make it even more interesting since bats operate in the same ultrasonic audio spectrum. Alternatives for ultrasonic microphones are relatively large and expensive, more than 150 dollars, which makes them unsuitable for the scope of the project. The microphone chosen uses an acoustic sensor and has a low noise input buffer. It performs best around the 20-30 KHz range due to an increased sensitivity, however it is relatively stable onward. [7] As seen earlier rodents operate around the 40-65 KHz sound spectrum, the microphone is a bit insensitive in this scope so an amplifier is recommended. In order to use the microphone a micro-controller should be used which is capable of sampling the analog signal with a frequency of at least 100 KHz. Due to these requirements the usage of the microphone is quite complicated. Therefore it is not considered anymore in the remaining of the research. However it is included in future work since it offers great potential for future research.

Temperature and humidity sensor. The DHT22 is a quite accurate and cheap temperature and humidity sensor. The sensor uses a capacitive humidity sensor and a thermistor for measuring the air surrounding the sensor. The data pin outputs the measured data in a digital format, so this can be directly connected to the Raspberry PI. The only drawback of the sensor is that you can only retrieve readings every 2 seconds. However in this project we only use it as addition for the dataset so it does not have to be accurate every second which makes it a suitable option for the project. It reads the temperature with an accuracy of ±0.5C and the humidity with ±5%RH which is more than sufficient for this application. [9]

4.2 Prototype

Secondly, we will discuss how the prototype is composed so that it meets all requirements. The main component of the prototype is the Raspberry PI model 4B 2 GB which functions as the processing core. The Raspberry PI has been chosen since it is able to process large amounts of data and process them on the client side due to the storage card which allows up to 32 GB of local storage and an 1.8 GHz quad-core processor. These features make it more suitable than for example an Arduino. Through the general output pins of the Raspberry PI the sensors have been connected. Almost all sensors could be directly connected except for the ultrasonic distance sensor which requires additional resistors and a breadboard to limit the current flowing back to the general output pin of the Raspberry PI. The radar sensor can also be connected directly to the Raspberry PI through the USB-port which was also tested, however testing the radar was easier through the laptop. Therefore for the prototype it was not included. To mount all sensors a plastified carton box has been used since it allows for easy adjusting of the sensors and is largely waterproof. In order to deploy the prototype in any remote area a power source is needed, for this sake a powerbank of 23800 mAh is used which allows for a runtime of over 12 hours.

Fig. 2. Physical Prototype

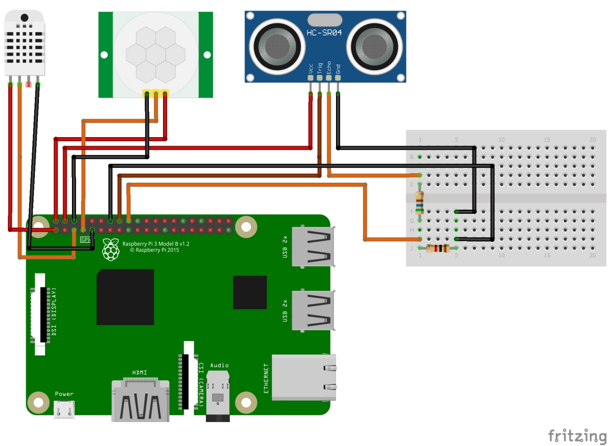

Fig. 3. Electronics scheme of prototype.

Looking at figure 2 it is visible that the ultrasonic distance and PIR sensor are horizontally aligned. This was done to ensure that they have the same line of sight. To record the same line of sight as the sensors, the camera has been placed in an elevated position above the PIR and ultrasonic distance sensor.

4.3 Software

In this part the software side of the prototype will be discussed. In order to run any kind of software the Raspberry PI needs to be installed with an operating system. For this purpose Raspberry PI OS has been chosen since it allows for a desktop which enables easy configuration and debugging. On the Raspberry PI VNC viewer has been used to easily connect from any device through the network to access files and code remotely. In addition the website app.remote.it has been used to even connect without being on the same network so the Raspberry PI is accessible from any location. However this feature increases power usage so if not necessary it should be turned off. In addition also the VNC viewer can be turned off to limit power consumption once a high confidence in the prototype has been established by running the script on boot offline

The scripts used in the prototype and for the sensor testing are all written in python. The standard IDE Thonny has been used to write scripts on the Raspberry PI. The main program is written in Python and uses a decision tree which is also shown in figure 4. The first step is to determine whether there is motion, if so it does an additional check whether the distance till the nearest object has changed. If the difference in distance is greater than the threshold it will go further down the decision tree. Once it is in the last stage it will know that there is an object in sight and it will start the measurements. The measurements will form a dataset consisting of a timestamp, IR-Picture, Ultrasonic audio recording, Distance till object or creature, temperature, humidity, temperature of Raspberry. Note that the ultrasonic audio recording is not possible as of now because of its high complexity but should be included in future iterations of the model.

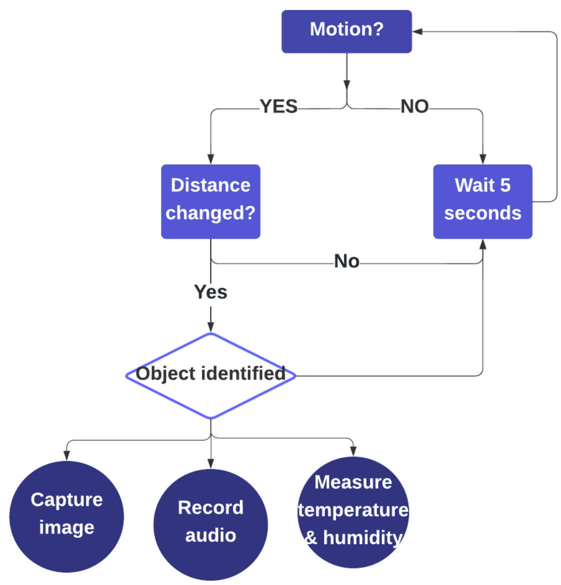

Fig. 4. Decision tree for main program.

4.4 Testing

Lastly in order to verify the performance of the prototype the testing phase has been split into two phases namely the individual sensor validation and prototype validation. In order to test the sensors individual performance metrics need to be established. In addition, also some test cases need to be established to verify whether the sensors perform the same under different circumstances.

Table 2. Sensor testing plan.

Sensor	Max. Dist	Accuracy	Error
PIR sensor	X	X	
IR Camera	X		
Ultrasonic distance sensor	X		X
Radar	X		X

Firstly the metrics chosen are latter the most important ones with respect to this specific application. The maximum distance is very relevant since it is important to know up to what range the sensor is reliable. The accuracy is relevant for the PIR sensor since it provides insight of how many positive triggers it would give when deploying the prototype. Lastly the error is used for the radar and ultrasonic distance sensor since they return numerical values which can eventually be weighted through error comparison.

Table 3. Definition parameters.

Metric	Formula
Accuracy	$\frac{Truepositive+Truenegative}{Allreadings}$
Absolute Error	$ABS(MeasuredValue - TrueValue)$
Mean Squared Error	$\frac{Error1^2+Error2^2+....+ErrorN^2}{N}$
Mean Absolute Error	$\frac{AbsError1+AbsError2+...+AbsErrorN}{N}$
Error Rate	$\frac{ABS(MeasuredValue-TrueValue)}{TrueValue} * 100$
Avg. Error Rate	$\frac{ErrorRate1+ErrorRate2+...+ErrorrateN}{N}$

The test cases which have been established are outdoors daytime, outdoors nighttime and indoors. This was chosen mainly to check the influence of light levels and the spacious effects of an indoor and outdoor environment on sensor performance. To simulate a moving target a RC car will be used with the following dimensions 28 x 16 x 17. For this project this was the smallest car available and resembles the size of the rodent. The RC car has an extra plate taped to the side to cover open spaces in order to simulate the solid body composure of the rodents which is necessary for the ultrasonic distance sensor. The RC car will be remote controlled to drive in front of the sensor on different distances. For the ultrasonic distance sensor and radar sensor a measuring tape will be used from which the true distance till the object can be read. The measured value as described in table 3 is considered the value which is given by the sensor. The true value is considered as the one that is read from the measuring tape. Since the RC car spans more than one centimeter in width the reading will be taken from where the plate crosses the measuring tape. An example of the test case is shown in figure 5. In these three scenarios the PIR sensor and ultrasonic distance sensor will be tested on 1,2,3 and if possible 4 meters since 4 meters is the expected maximum range of both sensors. The radar sensor will be tested with a different testing plan mainly since it uses a different technology which is more indifferent to influencing factors such as light levels. The radar sensor will be tested only outdoors during the day on the following distances: 1,3,5,7 and 9 meters. The sensor will be connected directly to the laptop and evaluated through mmWave demo visualizer, which is a website that allows to adjust the parameters and check results in a live environment.

Fig. 5. Test setup indoors from the POV of the prototype, RC car shown inside the red square

The prototype validation will consist of deploying the prototype outdoors to test whether it is able to run over an extended period of time. The most important metrics during this testing phase are the power consumption of the prototype and the accuracy of detection. In addition it would be relevant to check whether it is able to run for an extended period of time without human interference.

5 RESULTS

In this section the test results will be visualized and discussed.

5.1 Individual sensor testing

Firstly the results of the individual sensor testing will be discussed since this lays the foundation for future tests.

5.1.1 PIR Sensor. The PIR sensor was tested in the different environments as discussed earlier. Each scenario has been tested with at least 15 measurements. In order to minimize the impact of other sensors a separate script was used to solely test the PIR sensor. The PIR sensor was tested with the highest sensitivity possible, which means that the potentiometer was turned clockwise fully.

Table 4. PIR Accuracy.

Test case/Distance	1	2	3	4	Max dist.
Indoor	100%	93%	66.6%	13.33%	3 M
Outdoor daytime	100%	93.33%	66.6%	46.66%	4 M
Outdoor Nighttime	100%	86.66%	20%	0%	2 M

As seen in table 4 the performance of the sensor indoor is quite stable and slowly decays as the range increases. Considering the fact that the accuracy on 4 meter is only 13.33% it is clear that the maximum distance is set on 3 meters. The performance of the sensors outdoor varies quite a bit in the two different scenarios. During daytime the accuracy is higher on every distance. Around 1-2 meter the sensor seems to perform with a high accuracy but especially at nighttime it drops to only 20% which is relatively low. Therefore the maximum distance during nighttime is set on 2 meter. A possible explanation for this could be that during the nighttime the object reflects less infrared radiation which during daytime should be higher due to the sunlight falling on the object.

5.1.2 Ultrasonic distance sensor. The ultrasonic distance sensor was tested in the different environments as discussed earlier. Each scenario has been tested with at least 15 measurements. In order to minimize the impact of other sensors a separate script was used to solely test the ultrasonic distance sensor. The script sends out 100 pulses within 3 seconds to measure the distance till the object in front of it. Once it has received all 100 pulses it creates a list with all values and counts the occurrences. Then it will decide what the true distance is based on the following logic: Measured distance < Calibrated distance && Measured distance most occurring in list. This method is not taken from any earlier publications but was created within this research. Therefore further accuracy improvement is possible by tweaking the values of frequency of the pulses and the total amount of pulses.

Table 5. HC-SR04 avg. MAE.

Test case/Distance	1	2	3-4	Max Dist
Indoor	0.012	0.011	0.051	4.29 M
Outdoor daytime	0.042	0.081	0.093	3.42 M
Outdoor Nighttime	0.025	0.024	0.063	3.15 M

Looking at the results in table 5 we can clearly see that there is a difference between indoors and outdoors. On all distances the sensor performs better indoors than outdoors. Looking at close range, 1-2 M, we can see that the sensor reaches a high accuracy outdoors and indoors. However from 3 meters it starts to lose accuracy especially outdoors. From 3 meters onward the number of occurrences also dropped to a level where it only measured it once or twice, for this reason the maximum distance for outdoors is set on 3,24 M.

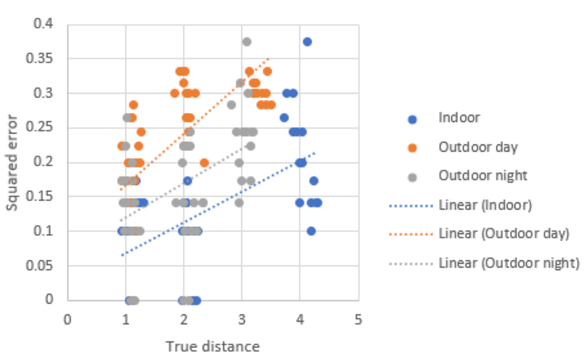

Fig. 6. HC-SR04 Mean Squared Error.

5.1.3 Camera. The camera was tested in two different scenarios namely nighttime and daytime outdoors. This was done since the light is one of the only factors influencing the camera performance. The camera will be tested by visual inspection since factors as for example sharpness on different distances or other numerical values are as of now not yet important enough and are time consuming. In a future development stage when image classification with machine learning is applied the camera can be tested and compared with the required numerical values.

Fig. 7. Test setup overnight.

Figure 7. shows the performance of the camera during nighttime with little to no additional light sources nearby apart from the IR-LEDS on the camera. The small bowl is placed on approximately 2 meters and is still sharp and visible. Structures on more than 4 meters away are also visible however they appear to be less illuminated by the IR-LEDS attached to the camera. One of the explanations for this could be that the temperature of the objects are low compare to the bowl which came from indoor where the temperature is higher. Another explanation could be that the range of the IR-LEDS is smaller than anticipated.

5.2 Radar

The radar sensor was tested using the mmWave demo visualizer software. The default parameters were mainly used. The only parameter that was changed was the "desired radar cross section" which was set to 0.25. The radar sensor was connected directly to the laptop and taken outdoors to check its performance. Since the radar has an higher estimated distance than the previous sensors, steps of 2 meters were taken as measurements starting at 1 meter.

Table 6. Radar avg. MAE.

	1	3	5	7	9	Max Dist
Outdoor	0.063	0.039	0.155	0.119	0.205	11.04 M

In table 6. the average MAE is shown on all distances tested. At 1-3 meters the radar is accurate with deviations of only 0.039 to

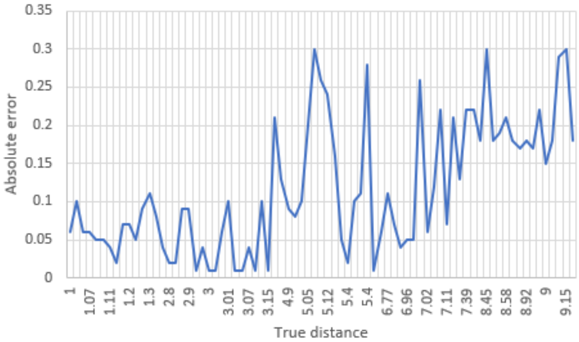

Fig. 8. IWR1642 Error on 1-9 meter.

0.063 meters. At 5 meters it starts to show higher deviations which are around 0.155. This performance was not anticipated since the prediction was that the radar would be accurate on all distances. On 7-9 meters it also showed some higher deviations than anticipated. One possible explanation could be that the strong wind on the day of testing caused some higher deviations, however this is an empirical observation from testing. In general, a trend can be seen in figure 8 which indicates the higher the distance, the higher the deviation. This would mean that it becomes less accurate on higher distances. Since the measuring tools to check the true distance did not allow more than 9 meters this was taken as the last measurement distance. However the car was detected by the radar on a distance of 11.04 meters so this is the maximum distance.

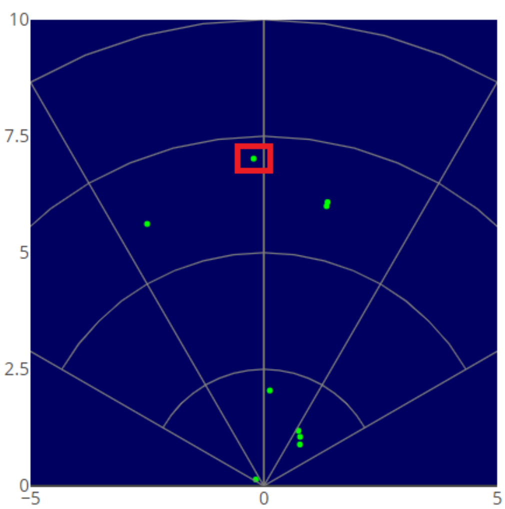

Fig. 9. Point cloud output of demo visualizer at 7 meters.

In figure 9 the point cloud is visible which is outputted by the demo visualizer. The red square represents the RC car which was detected. The other points visible are static clutter which, in the testing case, were objects like a big car, branches and some bricks. If the radar sensor were ever to be adopted the software should be able to remove this static clutter so that the only points visible are indeed moving objects. This could be troublesome in areas with more plants so this should be taken into account in future projects.

5.3 Prototype validation

During the prototype validation the aim was to deploy the prototype on a sight with a chance of capturing movement to see whether it is able to detect moving objects or creatures. In addition some other goals were to test the power usage and to check whether it is able to run for more than an hour.

5.3.1 First test. The first time the prototype was setup in the corner of a garden where a small plate with peanut butter was placed on a meter distance to attract animals. The prototype was elevated from the ground around 10-20 centimeters to protect it from ants and moisture. The prototype was launched and monitored through VNC viewer around 23:00 PM, however overnight it ran into some problems in the code. The main problem was that it would occasionally try to read a pulse which was not registered. Another bug found was that the PIR sensor sends a high signal to the pin every sixty seconds exactly even though there was no movement. As of now little knowledge is available on this problem, speculations are that this could be caused by voltage shifts on the pin due to the Raspberry PI communicating over WIFI.

5.3.2 Second test. The second time the prototype was set up in the same position as the first attempt. It ran from 23:00 PM till 08:00 AM, where the powerbank showed 100% power in the start and in the end 39%. The errors caused by the ultrasonic distance sensor were solved in this phase. In addition the PIR sensor again registered a high signal minutely, however this was used as an advantage. By sending a high signal minutely it allowed to capture pictures minutely, by doing this a baseline was created which was used to check whether the prototype missed any movement. On visual inspection some few small bugs were attracted to the bait but were not detected mainly due their size which is estimated to be around 1-2 cm. Around 5:00 AM some birds were recorded which were also attracted to the bait, however not all bird movement was recorded based off their movement. Some pictures were taken because of the bug of the PIR sensor. In table 7 the results are shown, in total there were 7 pictures taken with movement of which 5 were detected by the prototype. The 2 false negatives indicate that there was no movement but it still detected something. The 2 false negatives indicate that there was movement 2 times but no motion was detected by the prototype. Combining these results the accuracy can be calculated which rounds up to 55.56%.

The accuracy is quite low, one of the main reasons for this is that the prototype as of now only uses the PIR sensor as a check for movement and validates it with the ultrasonic distance sensor. Another option could be that both sensors check whether they detect movement and if one of both sensors detects movement it triggers. This would increase the TP and reduce the FN, however potentially could also increase the FP. Increasing the sensitivity of the PIR sensor would also increase the TP and reduce the FN, however potentially could also increase the FP. If more time was available some calibration could be done on the ultrasonic distance sensor which improves range and accuracy. Also two ultrasonic distance sensors can be used to increase the FOV since this is limited as of now to 15 degrees.

Table 7. Results prototype.

	True positive	False positive	False negative
Outdoor	5	2	2

Fig. 10. Bird detected by prototype.

6 CONCLUSION

In this research literature research and prototyping has been done in order to answer the main research question and its subquestions.

6.1 RQ1 Integration

This research has shown that there are multiple sensors which are able to capture different aspects of rodents behaviour. For that reason the call for a way to integrate various sensors was made. The research has shown that the ultrasonic distance and PIR sensor may lay the foundation as a trigger for the device to become active. After the device has been triggered the data must be captured which is done by the IR camera, temperature and humidity sensor and ultrasonic microphone. In order to capture ultrasonic sounds of rodents a small PCB or device should be created which is able to be connected to the Raspberry PI. Once the device is able to accurately identify rodents it can create high quality datasets which could be used for further processing. For example machine learning models and additional behaviour analysis can be applied which enables researchers to do further research towards rodents. In addition the radar sensor showed to be a high accuracy solution and performs well on higher ranges, therefore it could be used in further research and in higher level prototypes.

6.2 RQ2 Effectiveness of sensors

As seen in the results not all sensors perform as expected. The PIR sensor and ultrasonic distance sensor perform quite well in the range of 1 to 2 meters but their performance may lack in a range of more than 2 meters. The PIR sensor seems to be unreliable from 3 meters onward in daytime and from 2 meters in nighttime. The ultrasonic distance sensor also seems to become less accurate from 3 meters. Especially the reliability of the sensor is debatable over 3 meters. Looking at the prototype validation stage, it has shown that it is able to detect smaller size animals in the range of 2 meters with an accuracy of 55.56%. The accuracy is not extremely high but considering the fact that there was no calibration done and there is still room for improvement it shows to be a promising low-cost and low power consuming solution. In future designs the radar sensor can be integrated which shows to be able to detect smaller size moving objects up to 11 meters. The radar sensor performs around the same accuracy as the ultrasonic distance sensor in a range of 3 meters but loses accuracy on higher distances. However it still detects objects from 4 meters whereas the ultrasonic distance sensors does not detect objects from 4 meters. In conclusion, the radar sensor outperforms the ultrasonic distance sensor but is less feasible due to its high price and high power consumption.

7 FUTURE WORK

This research has laid out the foundation and blueprints for future development and research. There are many potential improvements and expansions to be made on the prototype as it is now. First of all one of the most important improvements is research into the microphone. Future research could entail a study on capturing rodent sounds through the use of relatively cheap microphones which are feasible for smaller size projects. Examples could be taken from bat sound capture projects, one of such projects is named Teensybat and is able to capture bat sounds at low cost. Once a feasible microphone is established, it could be integrated into the existing rodent detection prototype to make the dataset more complete. Secondly, future research could be done towards machine learning methods to identify rodents based on IR images. In order to achieve this, first a dataset has to be acquired with many IR images of rodents. Once this has been established it could be integrated within the existing prototype to improve accuracy. Lastly, the existing prototype which is presented in this paper could be improved in a future research. There are still a couple of bugs which are mentioned earlier which needs to be fixed. In addition the accuracy of the sensors could maybe be improved by more calibration or better software. By doing this the range of the prototype could be extended and a higher accuracy can be achieved.

8 ACKNOWLEDGEMENTS

I want to take this opportunity to specially thank Andreas Kalimaris for the support and supervision in the research. In addition I also want to thank Chirag Padubidri for providing technical insights and for his time and efforts.

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