Hedgehog Monitoring in a Wildlife Shelter Using mmWave Radar

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ABSTRACT

Sick or wounded hedgehogs are brought to wildlife shelters for rehabilitation. These hedgehogs' health needs to be monitored for eventual re-release into the wild. Many common sensing solutions are either unsuitable or too expensive. This paper explores the potential of using millimetre-wave sensors to localise and track hedgehogs within their enclosures. This was done by comparing millimetre wave sensors to infrared and regular cameras. The comparison shows that more research is needed for the millimetre wave sensor. The regular camera does not function properly in low-light environments. Finally, the infrared camera performs exceptionally well.

KEYWORDS

Millimetre wave, hedgehogs, point cloud, infrared

1 INTRODUCTION

Wildlife shelters play a vital role in providing safe environments for the rehabilitation and care of hedgehogs and other small wild animals. When a hedgehog in distress is found, an animal ambulance must be called to help the animal. These ambulances, mainly operated by volunteers, transport the wounded or sick hedgehog to a local rescue facility [3]. Rescue facilities of the Dutch animal protection organisation take in an average of 1300 hedgehogs yearly. Due to the high number of hedgehogs that need care, the rescue facilities become overfull. Thus, the most feeble hedgehogs do not get the care they need [1]. This highlights the need for adequate rehabilitation to speed up recovery and free up shelters more quickly. In these pet shelters, hedgehogs are often housed in enclosures designed to mimic natural conditions, providing protection and support. For instance, sufficient food and water, a heating pad, nesting materials, and a covering to darken the enclosure [4]. However, a successful recovery requires much more than a good shelter. Monitoring the health and well-being of these animals is critical to ensure their successful recovery and eventual release back into the wild. Unlike most animals cared for in pet shelters, such as cats or dogs, hedgehogs are unique due to their small size and primarily nocturnal nature. These unique characteristics pose multiple challenges when monitoring the condition and health of rehabilitating hedgehogs.

Currently, health monitoring for hedgehogs in pet shelters happens manually. Frequent handling is avoided to prevent causing more stress to an already vulnerable animal. Moreover, the hedgehog's predominantly nocturnal lifestyle means that signs might go unnoticed by staff since they only check in during the day due to their working hours [4].

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When monitoring hedgehogs and other small animals, common sensing methods are not suitable for use in a pet shelter setting. Light (camera) may disturb the natural rhythm of the animals, Wi-Fi radio waves are too coarse-grained (long wavelength) to capture small movements, and other solutions (such as thermal cameras) are expensive. Due to these challenges, a non-invasive continuous monitoring system is needed. Emerging technologies, such as millimetre-wave (mmWave) sensing systems, might be suitable for real-time tracking of health indicators. Implementing such a system in a pet shelter may increase the efficiency of rehabilitation for hedgehogs. Using shorter wavelengths, such as those employed by mmWave radar systems, offers a promising solution for continuous, high-precision monitoring of hedgehogs (and other small animals). mmWave sensors are particularly suited for detecting subtle movements and changes in behaviour without intruding on natural patterns. mmWave radar uses extremely high frequency, which allows for detecting small movements through obstacles like bedding. Unlike cameras, mmWave sensors can function well in low-lit environments. mmWave sensors provide continuous point clouds, enabling the analysis of well-being indicators such as activity levels and movement patterns associated with restlessness, pain or distress. By integrating this technology with embedded machine learning systems, it is possible to analyse data locally and deliver actionable insights while minimising energy consumption and processing delays.

1.1 Research Questions

The problem statement leads to the following research question:

- To what extent can hedgehogs accurately be localised and tracked using mmWave radar sensors in wildlife shelter enclosures?

The main research question can be answered with the following sub-questions:

(1) What is the best location for a mmWave sensor to gather data in a hedgehog enclosure?
(2) How does the mmWave radar sensor compare to infrared and regular camera?

This research will investigate the possibility of localising and tracking hedgehogs using mmWave radar technology. This is done by analysing the data from the mmWave sensor and comparing the results to those of an infrared camera and a regular camera. This paper provides insights into the level of accuracy that mmWave radar sensors can achieve in small animal localisation and tracking.

Firstly, this paper will disclose related work on mmWave sensing technologies and studies on animal detection using various strategies. Secondly, the tools, materials, and environment used for data acquisition and analysis are described. Thirdly, the results of the data analysis will be discussed. Lastly, this paper will discuss the challenges, outline further work, and highlight key takeaways.

2 RELATED WORK

2.1 Millimetre wave applications

Millimetre wave is widely adopted and can be used for many purposes. The most well-known example is the 5G cellular network [17]. Some examples of other well-studied applications are, firstly, the automotive industry, with uses in self-driving cars [23], traffic monitoring [9], and incident detection [21]. Secondly, security and surveillance applications include hidden electronics recognition [14], multi-person tracking [24], and device-based localisation [20]. Lastly, the human healthcare sector, with applications like vital sign detection [13], rehabilitation systems [5], and health monitoring [25].

2.2 Animal tracking

Little research has been done on localising and tracking small animals, such as hedgehogs. Several studies have been done on the localisation and tracking of humans. Furthermore, some studies delve into localising and tracking larger animals using mmWave, like sheep and other livestock. In 2020, Dore et al. [8] discuss behaviour tracking in sheep. Similarly, Henry et al. [10] studied the use of Frequency-Modulated Continuous-Wave (FMCW) radars to automate the monitoring of livestock behaviour.

In the research by Mattos et al. [16], the detection of small animals in addition to humans is tested. However, the smallest animal tested on is a dog, which is several times larger than a hedgehog.

The work by Bearman-Brown et al. [6] compared different non-invasive localisation techniques for hedgehogs in their natural habitat. One of the methods is the use of an infrared camera, which has shown promising results in specific natural habitats.

2.3 Activity recognition

In the area of activity recognition, Van Raalte [22] analysed whether recognising the activity of animals (in particular dogs) is possible using mmWave radar. This paper predominantly describes the challenges and limitations of the techniques used. Other challenges include obtaining reliable training data for an AI model from animals. This is primarily due to a lack of training data, as animals cannot present particular behaviour on command.

In their 2021 research, Liu et al. [15] present a perspective on pet emotion motoring using mmWave radar. This research presents a hopeful approach to detecting emotions using mmWave. Although pet emotion monitoring is a relatively new concept, further research is needed.

3 DATA ACQUISITION

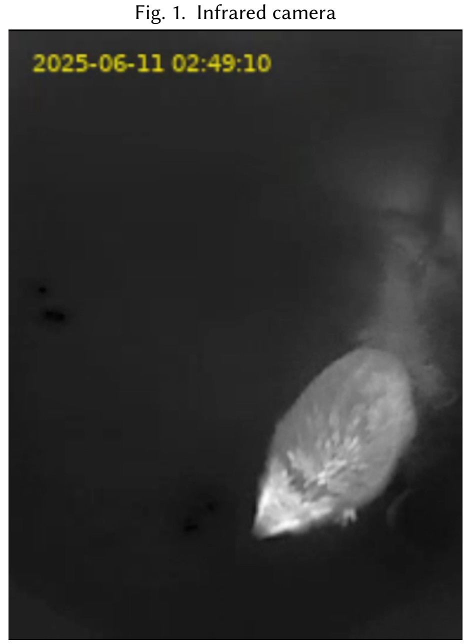
3.1 Millimetre wave radar

Millimetre waves are short-wavelength electromagnetic (radio) waves. The frequency range is typically defined as 30 GHz to 300 GHz, and the wavelength lies between 10mm and 1mm [19]. Radar systems emit electromagnetic waves, which are reflected by objects in their path. The system can determine the range, velocity, and angle of the objects through the captured reflected signal. As mentioned earlier, the wavelength is viewed as short within the electromagnetic spectrum. One of this technology's key advantages is its high accuracy. A mmWave system operating in the 76–81 GHz range (with a corresponding wavelength of approximately 4 mm) can detect movements as small as a fraction of a millimetre [12]. Using small wavelengths results in good detection of small movements because slight changes in position cause significant changes in the wave's phase. The mmWave radar sensor used for this research is Texas Instrument's IWR6843 antenna-on-package (AoP) evaluation module (EVM). This sensor was used in combination with the MMWAVE-ICBOOST carrier card. The firmware used for the mmWave sensor was the Radar Toolbox demo firmware. This firmware can be used in combination with the TI mmWave demo visualiser.

3.2 Infrared camera

There exist two types of infrared thermal imaging: active and passive. With active infrared devices, a sender emits continuous infrared radiation. A person or object passing through the infrared beam reflects or interrupts the light. These signals are then sensed by receivers that detect these reflected or interrupted infrared beams. On the contrary, passive infrared devices themselves do not emit infrared radiation. Instead, the infrared device detects radiation emitted by people or objects. When a person or object enters the detection range of the passive infrared sensor, it affects the infrared energy pattern, triggering the sensor to detect the change [2]. This research used a passive infrared camera, specifically TOPDON TC001. An example frame of such a recording is shown in Figure 1.

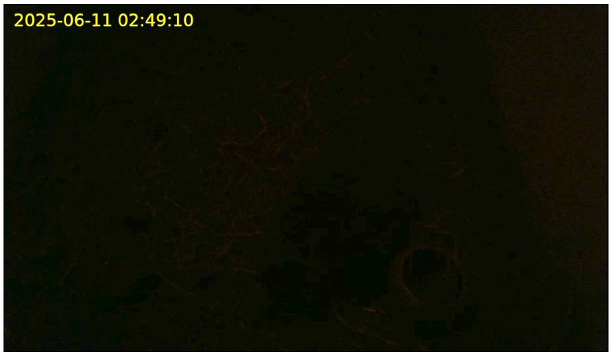
Fig. 1. Infrared camera



3.3 Camera

Another addition to the test setup is a regular camera. The camera output was dark since the data acquisition happened in a low-lit environment. For this reason, a colour correction was added to the output stream so that the hedgehog would be better visible. An example frame of such a recording is shown in Figure 2.

Fig. 2. Regular camera



3.4 Environment

The data collection process was the result of careful planning and consideration of the hedgehog's nocturnal behaviour. The mmWave radar was strategically positioned overhead, approximately 0.6 meters from the enclosure's bottom. Similarly, the infrared and regular cameras were suspended at the same distance but at an angle to maximise the field of view (FOV). This setup ensured that the cameras had a similar view, enhancing the consistency of our data. Notably, the data was gathered from a single hedgehog, and the sensors and cameras were mounted side by side for simultaneous data recording.

4 METHODOLOGY

A Raspberry Pi was left at the testing location since the data collection happened overnight. All of the sensors and cameras used were connected to this Pi. An SSH tunnel was set up on the Raspberry Pi to allow remote access to the Pi. The video footage from the IR and regular camera was live-streamed using the RTSP protocol to reduce latency. This livestream could then be recorded on a machine with a larger disk size for later analysis. The IR and regular camera recordings were captured using OBS on an off-site PC. A timestamp was added to the stream using ffmpeg to ensure that the sensors could be compared. The mmWave radar sensor data was also provided with a timestamp and saved to a binary file on the Raspberry Pi for later analysis. A diagram of the experimental setup can be found in Figure 3.

OpenCV was used to detect and track the hedgehog in the Infrared video. The script detects objects above a relative temperature threshold and draws a bounding box around the object. The same technique was intended for the regular camera output. However, due to the lack of light, there was too much noise to make a reliable measurement. An example frame from the OpenCV output is shown in Figure 4.

A visualiser was developed to process the recorded mmWave binary data file. This tool was used to both visualise and analyse

Fig. 3. Experimental setup

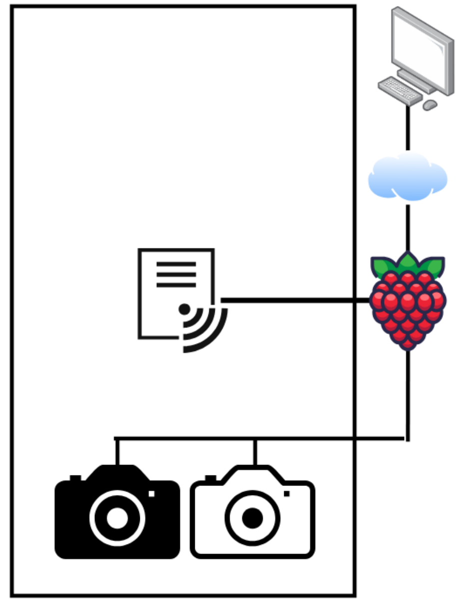
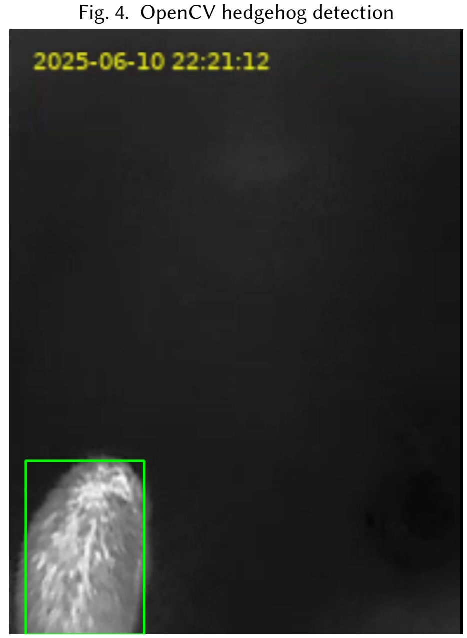


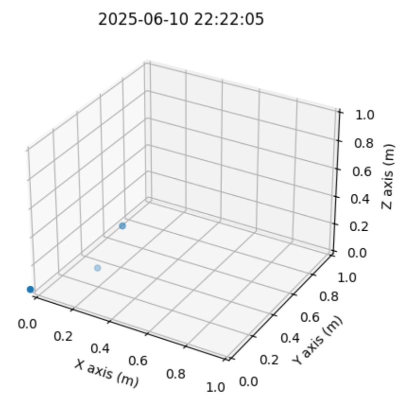
Fig. 4. OpenCV hedgehog detection



the acquired mmWave data. The visualiser utilises the matplotlib library to display the mmWave point cloud data in a 3D scatter plot. An example frame is shown in Figure 5.

For the analysis, 50 data samples were used. These samples, each almost 1 minute long, were randomly selected from the recordings. Only data samples where the hedgehog was in view of the cameras were used. Otherwise, no comparison could be made between the cameras and the mmWave sensor. This meant that out of the 50 data

Fig. 5. mmWave visualiser



samples, 41 samples were analysed and compared to the mmWave sensor data. A diverse range of samples were used to test for distinct locations within the enclosure to evaluate performance metrics.

4.1 Evaluation metrics

The following metrics were used for the evaluation of the data from the mmWave sensor, the regular and infrared camera.

- Positives (P): Hedgehog present in the detection area.
- True Positives (TP): Hedgehog in detection area that is successfully detected.
- False Positives (FP): Noise or other objects in the detection area that are falsely detected as hedgehog.
- Sensitivity (TP/P): The ability to detect a hedgehog when present in detection area.
- Precision (TP/(TP+FP)): The ability to distinguish a hedgehog from false detection.

Ideally, the sensitivity and precision should be as high as possible [7][16].

5 RESULTS

	Sensitivity min/avg/max	Precision min/avg/max
Normal camera	0%/0%/0%	0%/0%/0%
Infrared camera	100%/100%/100%	50%/94.2%/100%
mmWave sensor	NA	NA

Table 1. Metric evaluation

5.1 Normal camera

Obtaining valuable data at night was challenging due to the insufficient light for the regular camera. The only source of light was the LEDs of the mmWave sensor. By amplifying this light, the output could be processed. However, the hedgehog was only visible when it was in the spot that was illuminated by the LEDs. When the sun had risen, more light made it possible to localise the hedgehog when the view was not obstructed by hay. This occurred during only one of the data samples. This meant the the hedgehog could not be tracked using OpenCV, which is why the sensitivity and precision are 0%.

5.2 Infrared camera

The infrared camera accurately localised the hedgehog in all of the data samples, meaning a sensitivity of 100%. Since the hedgehog was always accurately localised, the lowest precision was 50%. This means that in that data sample, the false positive rate was as high as the true positive rate, so 100%.

5.3 mmWave sensor

The mmWave sensor data was not usable for data analysis. The point cloud data was too sparse and this could not be fixed due to time constraints.

5.4 Example

To illustrate the data output, a sample of the data is used as an example. The camera, infrared, and mmWave outputs can be seen in Figures 6, 7, and 8, respectively. In this data sample, the environment had started to lighten, making the hedgehog visible. However, since the hedgehog was tossing some hay, there was too much noise for the OpenCV script to localise the hedgehog. The infrared camera registered a false positive for the spot that the hedgehog had been in for a while, as well as a true positive for the position of the hedgehog. In the output from the mmWave sensor, it can be seen that there are few data points to work with. Which one of the three is the actual location of the hedgehog is not deducible from this single frame of data.

Fig. 6. Example camera

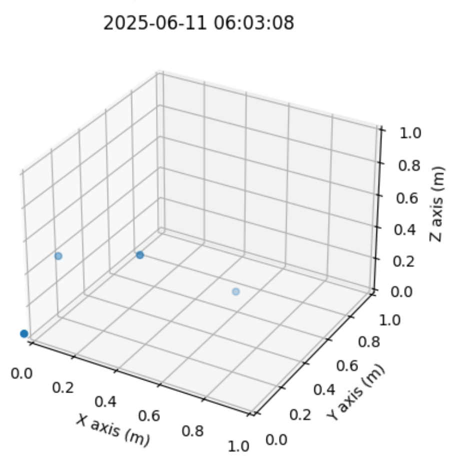
6 DISCUSSION

6.1 mmWave placement

A document from Texas Instruments, the maker of several mmWave sensors, was consulted about the placement of the sensors. The scale had to be adjusted since these guidelines were written for indoor person localisation and not for animals. According to this document [11], it is recommended to hang the sensor as high as

Fig. 7. Example infrared

Fig. 8. Example mmWave



possible. Since the hedgehog enclosure is rectangular, mounting the sensor in a corner or on the wall would result in some areas with low detection rates. Since a wall mounting would not work, an overhead mounting was chosen. When mounting the sensor on the ceiling, the optimal angle is 90 degrees from the horizontal, with the sensor pointing directly at the floor. Mounting the sensor overhead, centred at a 90-degree angle, is the recommended method for small conference rooms and office cubicles. These rooms, downscaled relatively to the size of a hedgehog, closely resemble the size of the enclosure. The sensor used in this research is also the best option with this mounting method. According to the formula mentioned in this document, the entire enclosure is within detection range.

6.2 Infrared

The IR camera consistently demonstrated its reliability in localising the hedgehog, never failing to track its position. This is evident from its 100% average for the sensitivity metric. This indicates that in all data samples, the hedgehog was successfully localised and tracked using the infrared camera, even when it was fully buried in hay. The false positives from the infrared camera can be attributed to one of two things. There was either a warm spot where the hedgehog had been for a while, or the infrared camera picked out excreta. This is because both of these were similar in warmth to that of a hedgehog. These false positives can likely be filtered out by altering the OpenCV script. One possible solution could be to allow only one box on the screen at a time, but this would not work when the hedgehog is out of view. Alternatively, motion detection could be implemented. However, this would not work when the hedgehog is sleeping or lying still for extended periods.

6.3 mmWave

In contrast to the infrared, the mmWave point cloud data was inconclusive about reflecting the hedgehog's position in any of the cases. Locating the hedgehog with the visualised mmWave data was not possible. This was mainly due to the sparse point cloud density. In some instances, the sensor failed to detect any points. When the sensor detected points, they were often few and appeared to be randomly scattered across the plot. Presumably, this inconsistency was because of the high number of reflections, since these points did not correlate with the position of the hedgehog. One of the captured points was around 0.005 meters away from the sensor. This point was likely the tie wrap used to attach the mmWave sensor to the enclosure.

6.4 Camera

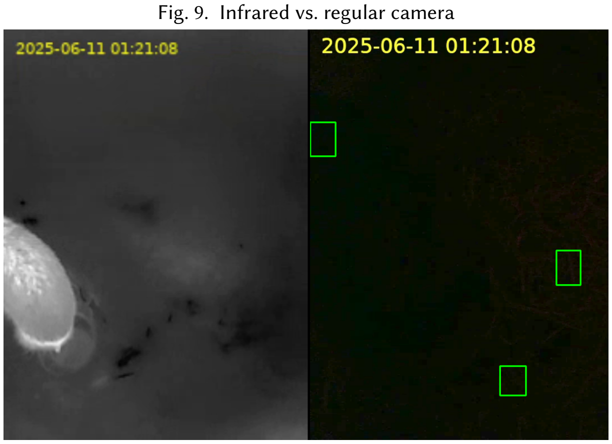
The first time the camera was tested overnight, it quickly became apparent that the output would be too dark to be usable. The colour correction filter was designed to increase visibility. The light emitted from the LEDs on the mmWave sensor was amplified in the video footage. This way, the footage could be processed, but the hedgehog was only visible at night when in the LED lighting. Tracking the hedgehog using the standard camera was challenging during the night, even with the human eye. The low visibility made it difficult to determine the hedgehog's position in the footage captured by the regular camera. Tracking with the regular camera, without external light, was made possible only by correlating with the infrared footage. The importance of prior knowledge of the hedgehog's location in making the detection and tracking possible with the regular camera cannot be overstated. Without this, locating the animal would have been considerably more difficult, if not impossible. The hedgehog was visible during one of the samples. Here, the sun had already risen enough to illuminate the enclosure. In the other samples, where the environment was light enough, the hedgehog was camouflaged by a layer of hay.

6.5 Comparison

The same method used to evaluate the infrared footage was also intended for the camera footage. This was tried using a similar

OpenCV script. However, this was not possible in any of the data samples. When fine-tuning the threshold for detection, there was either too much noise, resulting in many false positives, or no detections were made. An example is shown in Figure 9. On the left side, the infrared camera footage is shown without a bounding box. On the right side, the regular camera footage is shown. Both cameras show the same portion of the enclosure. As can be seen, there are some false positives; however, none of them accurately reflect the hedgehog's position. Since the data from the mmWave sensor and the regular camera could not be analysed effectively, there can be no comparison between the three. The only clear thing is that in the current state, the infrared camera is the superior option for localising the hedgehog.

Fig. 9. Infrared vs. regular camera



7 CONCLUSION

This research examined the mmWave sensor's capability to localise and detect hedgehogs in a wildlife shelter environment. This was achieved by comparing the mmWave sensor to state-of-the-art solutions, including regular and infrared cameras. The best location for a mmWave sensor to gather data in a hedgehog enclosure was to mount the sensor centred, overhead, and pointing down. The mmWave radar sensor data could not be effectively compared to the output of the infrared and regular cameras. Although the footage from the infrared camera was quite good, the data gained from the mmWave sensor was challenging to interpret. The output from the regular camera was too dark in the low-lit environment to discern anything. The best option out of the three was the infrared camera. For a comparison between mmWave radar sensors and infrared and regular cameras, further research is needed. The same applies to the extent of accurately localising and tracking hedgehogs using mmWave sensors in wildlife shelter enclosures.

7.1 Limitations

For the data analysis, not the full overnight recording was used, which was over 10 hours long and too extensive to analyse manually. Instead, 50 random samples were selected from the recording. This approach enabled the study of a wide range of distinct scenarios, including walking, standing, lying still, and obstructions caused by nesting materials.

The infrared camera, although effective, had some limitations. It would regularly pick up excreta from the hedgehog, as this is the same temperature as its body. It also occasionally registered places where the hedgehog had lain for an extended period. However, these issues are not insurmountable. By modifying the OpenCV script to filter out non-moving parts of the frames, performance may be enhanced.

Working with mmWave sensors in the context of animal tracking presented its challenges. These sensors are complex and lack adequate documentation, especially in this relatively new field of research. As a result, significant challenges were faced in developing a visualiser and interpreting the sensor data. Due to time constraints, a substantial amount of time was dedicated to the initial setup and understanding of the output. Unfortunately, due to the limited time available at the testing site, the mmWave sensor could not be optimally calibrated, making the acquired data challenging to interpret.

The mmWave sensor's user-friendliness was a stark contrast to the ease of setup of the infrared camera. Not only was the infrared camera easy to get started with, but it was also enjoyable to watch the video stream.

7.2 Future work

Due to the limited time, some ideas were not yet explored in this research. Nevertheless, they could be interesting to research further. One of these ideas is to develop custom firmware for the mmWave sensor to fit the specific application of tracking small animals, such as hedgehogs. This custom firmware can enhance the sensor's capabilities, enabling more precise and efficient tracking compared to the currently used firmware. Another idea is to use a metal rod or another reflective object around the perimeter of the animal's enclosure to set the dimensions for the mmWave sensor. This could calibrate the sensor to ignore points outside of these set boundaries, thereby reducing noise in the data and improving the accuracy of the tracking.

One potential solution to address the issue of sparse point clouds is to cluster multiple mmWave point cloud frames. In this research, the sensor was configured to capture 10 frames per second. Given the relatively slow movement of hedgehogs, this approach could significantly increase the volume of data available for analysis. After increasing the density of the point cloud, a clustering algorithm, such as DBSCAN, could be used to filter out noise. Additionally, an AI model could be trained on the mmWave data that has been labelled using infrared footage as ground truth. This process involves feeding the labelled mmWave data into the AI model, which then learns to identify patterns in the data that correspond to the features of a hedgehog. Once trained, this model can help identify patterns in the mmWave data that are difficult for humans to discern.

During hibernation, a hedgehog's body temperature can drop to about 6.5 degrees Celsius while inactive [18]. This could pose a problem when localising a hedgehog using infrared technologies.

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