RoadMic: Road Surface Monitoring Using Vehicular Sensor Networks with Microphones

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Abstract. Road surface analysis including pothole reports is an important problem for road maintainers and drivers. In this paper we propose a methodology for pothole detection using mobile vehicles equipped with off the shelf microphone and global positioning devices attached to an on-board computer. The approach is generic enough to be extended for other kind of event detection using different sensors as well. The vehicles are driving on public streets and measuring pothole induced sound signals. Our approach was tested and evaluated by real world experiments in a road segment for which we had established the ground truth beforehand. The results show pothole detection with high accuracy despite the background noise and other audio events.

Key words: road surface analysis, microphone, vehicular sensor network

1 Introduction

Sensor networks deployed on vehicles offer a wide range of features while not being constrained by severe energy, memory and computational limitations in comparison to the regular wireless sensor networks that are battery powered. This opens a new field of applications with more resources for data processing and storage. In addition, high vehicle mobility provides data from large geographical regions that is collected with significantly lower count of sensor modules and in shorter period of time. However, the highly dynamic behavior of vehicular sensor networks has influence on the measured data. Compared to the static measurement approach with stations at predefined locations, higher noise level and dynamic range of the signal characteristics are expected from the sensing platforms moving at high speeds in a heterogeneous environment, implying higher signal processing requirements.

Such a sensing system may record sound by mobile microphones in order to build urban noise maps [9] or detect different events on the street, including potholes, emergency vehicle proximity or overall vehicle density. Initially, the system is adopted by car enthusiast community that is extended by vehicles of public transportation and taxi cars. For this to be feasible, the system must feature hardware availability at low costs and limited maintenance requirements. For example, there are portals for pothole detection and registration by the community such as potholes.co.uk [1], where this sensing system would function as the data source for the pothole data base.

This paper is addressing the following research problem: what data quality in terms of road surface quality could be achieved by recording and processing sound in a moving vehicle using regular off the shelf audio microphones. We propose an approach for pothole detection using distributed vehicular sensing system. In addition, our approach is generic and usable for diverse event detection using different sensors. We present a measurement study describing characteristics of a vehicular audio-sensor platform and draw conclusions about the event detection accuracy.

Measurement studies in the area of vehicular, people centric sensing and mobile sensing in general have already been done previously. SoundSense [6] is a framework for sound event modeling on mobile phones, proposed by Dartmouth College. However, this framework is not intended for use in vehicular contexts. BikeNet [4] from the same research group is a mobile sensing system for cyclist experience mapping. Among other sensors it is using microphone to estimate the quality of a bike ride. The microphone is used only to assess surrounding noise level in dB. In contrast, we perform a more sophisticated examination of the audio signal. Nericell [7] is a platform for pothole, bump, honking and braking detection by a mobile phone that located in a vehicle. Sound frequency domain is searched for spikes to detect honking, however, it is not used for pothole detection. Pothole Patrol [5] is a vehicular sensor network platform for road quality estimation and reporting using on-board computers with accelerometers, GPS and WiFi access - it detects a particular kind of events on the road, but does not consider using a low cost microphone.

This paper is a step towards a vehicular sensor system that goes beyond simple audio capture and threshing. We anticipate using more sensors tailored to the particular applications, where using a cellphone like in the Nericell project [7] would be insufficient. Also, the cellular phones often do input audio filtering and preprocessing to eliminate the noise, which would be unacceptable for our system requiring a microphone signal with wider audio bandwidth.

We performed real world experiments of pothole detection using microphone in a controlled area. We marked irregularities in a road segment, performed test drives and offline sound analysis by thresholding. The results of our evaluation show that potholes are detected by our method with high accuracy. Threshold adjustment is a trade-off between sensitivity and accuracy - lower thresholds produce more potholes with moderate probability, higher thresholds find less potholes with higher confidence.

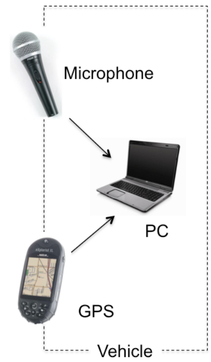

Fig. 1. Vehicle on-board sensing system architecture

2 Our approach

We set the following practical requirements to our vehicular sensing system which are important for system acceptance by a wide user community:

- Low setup and maintenance costs. Expensive sensors and processing systems are not required, as are not cellular data plans for large volume of data transmissions
- Availability of used hardware components. System must consist of off-the-shelf components available in a regular electronics shop
- No programming and administration skills are required for users
- General-purpose computer is required for data logging, mobile phone is also an acceptable alternative if it is able to store and process the data. Laptop seems to be the most appropriate and accessible device at this time. Any kind of embedded devices is acceptable as long as it supports any of the used operating systems
- Wide range of supported sensors in addition to the microphone. Interface between sensors and the PC is not specified
- Software platform independence. All the most popular desktop operating systems should be supported, including Windows, Linux and MacOS
- System must be able to function in environment with light rain, snow and wind. Work in extreme conditions (hurricanes, under water) is not required
- Localization service is required for data geo-tagging
- System must be able to store several gigabytes of data and process it on-the-spot, in real time, with reasonable latency, which depends on the application. We recognize, that audio signal with low sampling rate does not have large storage space requirements. However we envision other sensor data, including video stream, processing in the future, therefore a several megabyte flash storage could be insufficient in general case

Based on requirements, we define architecture for our vehicular sensor network system, as shown in Figure 1. Microphone is the only used sensor at the moment, but other sensors are allowed. GPS and microphone are connected to a PC. All these components are located inside the vehicle, but sensors and GPS can also be attached outside it. GPS is, in our opinion, the best alternative for localization in vehicular context in terms of price and accessibility.

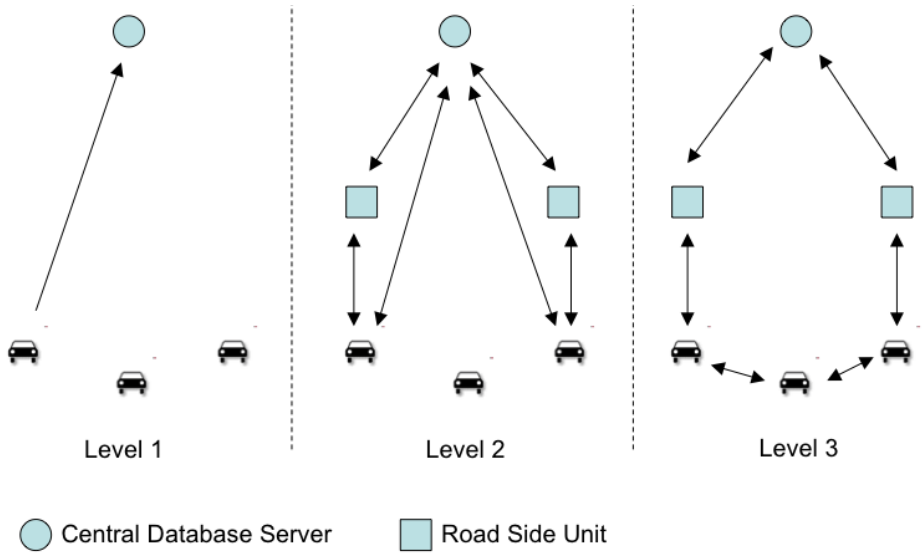

Fig. 2. Our vision of vehicular sensor network communication paradigm evolution

We describe the generic algorithm for location and time based event detection from recorded sound in a driving car:

1. record GPS trace and sound simultaneously
2. interpolate position between two GPS fixes, which typically have a granularity of one second
3. discretize the sound signal with lower frequency to reduce sample count, high frequencies usually contain no information and can be discarded as noise
4. assign geographical coordinates for sound fragments, which also represent a small geographical region
5. perform event detection function for each region, using digital signal processing (DSP) which is specific for each class of events

In particular, for pothole detection we use the following parameters:

- sound discretization with frequency 200Hz
- thresholding as pothole detection function

For evaluation we have used signal with 96kHz discretization frequency. But we have established, that potholes induce vibrations of low frequencies. Therefore, to save storage space in case of on-line signal processing, discretization of 200Hz is enough to be used in the future.

Table 1. Ground truth parameters

Parameter	Value
Test track length	4,4km
Large pothole count	3
Small pothole count	18
Pothole cluster count	30
Gap count	25
Drain pit count	29
Total roughs:	**105**

For sensing system to become a sensor network, communication layer is required. We envision the evolution of vehicular sensor network communication with the central database server as depicted in Figure 2. The first level is direct communication, mainly upload, using cellular technologies, for example, EDGE/GPRS. This is the best approach, when data reports are small (in order of KB) and only a few vehicles are participating. When data amounts are in order of megabyte, road side units or public access points [3] acting as intermediate agents improve the communication (level 2). Also download becomes more important - vehicles download updates and reports, and receive tasks from the server. At a scale where nearly all vehicles are equipped with sensing and data report system (level 3), central server can hardly withstand the load of direct communication. At the same time, it becomes feasible to use vehicle-to-vehicle communication for data dissemination. A more comprehensive communication architecture study is available in our previous work [8].

In this paper we describe a methodology, rather than end-to-end solution. We have built the first prototype of our vehicular sensing system. Communication to central database server is part of future work and is not examined at the moment. All the data processing in our evaluation studies has been done offline. It is, however, important to understand, that our approach is a sensor network, and that conclusions about the environmental phenomena can be drawn only when having reports from multiple sensor agents - vehicles.

Table 2. Test drive parameters

Parameter	Value
Drive count	10
Total duration	1h53min
Total distance	43.53km
Max speed	59.81km/h
Avg speed	24.01km/h
Microphone type	Electret
GPS receiver	Magellan eXplorist XL
Car model	Volkswagen Sharan
Laptop model	Acer Extensa 5230

Fig. 3. First examined road segment with pothole

3 Evaluation

To evaluate our approach we performed experiments with pothole detection from sound recorded in a car driving in urban environment. We started with hypothesis, that recorded sound has a correlation with road surface irregularities. To get the first impression of how to detect a pothole in audio signal, we found a particular road segment with pothole shown in Figure 3 and recorded sound while driving along it. We discovered, that pothole has a footprint of high amplitude of low frequency oscillations in sound signal, see Figure 4. Therefore we chose thresholding by amplitude as pothole detection method.

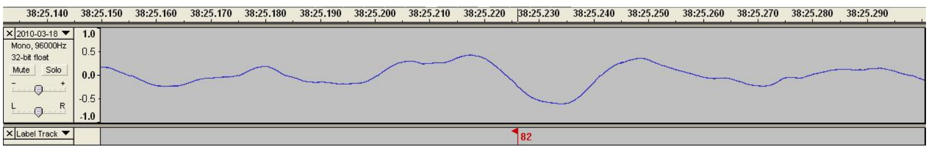

Fig. 4. Sound of test segment with pothole position marked, 96kHz sampling frequency (Audacity [2] used)

Fig. 5. Experimental test track, 4.4km long, with manually marked road roughs

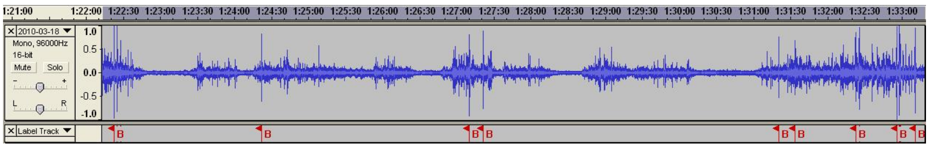

Fig. 6. Sound of one test lap with detected pothole positions using 50% threshold, 96kHz sampling frequency (Audacity [2] used)

To validate our hypothesis, we performed a series of controlled test drives in a real world environment. First we established the ground truth by manually marking road irregularity coordinates using GPS while walking along the street. All irregularities were divided into 5 classes: large pothole, small pothole, pothole cluster, gap and drain pit. The ground truth parameters are shown in Table 1 and the map with marked road roughs is shown in Figure 5.

We performed 10 test drives, recording sound, using Audacity [2], with microphone attached to a laptop, located in a car. All the test drives were performed during the same day. In one of the 10 rides music was playing inside the car. We noticed no significant impact on event detection during that ride, an explicit comparison is not included in this paper. Parameters of test drives are listed in Table 2.

Offline pothole detection was performed, by using thresholding by amplitude for the recorded sound and establishing geographical positions of potential potholes. Recorded sound of one test lap with detected pothole positions marked are shown in Figure 6.

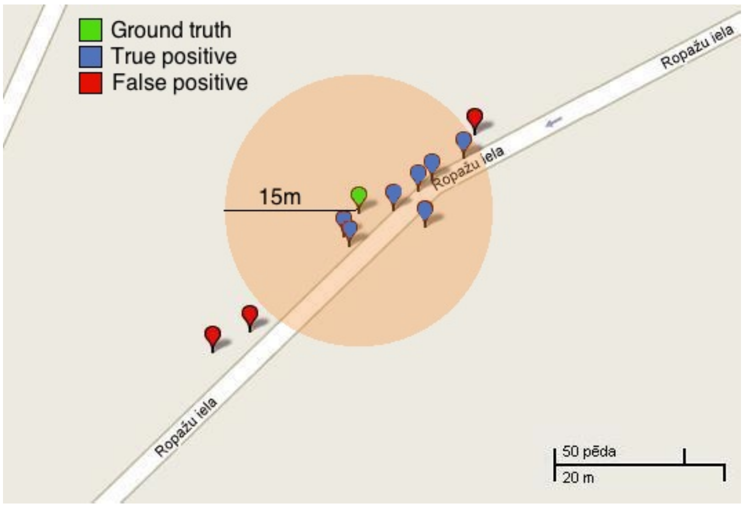

Fig. 7. Pothole positions detected using sound analysis around position marked as ground truth. Positions not further than 15m are considered true positives

To estimate our detection algorithm, we compare the distances between potholes detected by using sound analysis and potholes manually marked as ground truth.

When estimating accuracy of our approach, we have to take GPS localization precision into account. We intentionally used a regular GPS receiver accessible to an average car driver. We do not require system users to have a military purpose, high accuracy GPS receiver. Therefore we assume a standard GPS position fix period of 1 second and position estimation accuracy of ± 3-30 meters. In our experiments, the experienced GPS accuracy median was ± 10-15m. In this evaluation we use these median values but in the future our approach could be extended by using accuracy data of every discrete GPS position fix, reported by the GPS device. The car was driving, with few exceptions, at speeds up to $50km/h \approx 14m/s$. The overall typical position estimation accuracy in our tests is assumed ± 15m - maximum of the two above mentioned.

We define, that pothole position extracted from sound signal is a positive match of a real pothole if the distance between the two is not greater than 15 meters. This is a rather conservative requirement, as the localization accuracy may be far worse in some cases. Figure 7 shows an example of ground truth pothole position with positions detected from the sound in close proximity of it: 7 of 10 detected positions (70%) are considered true positives, 3 of 10 - false positives (30%).

We performed detection using different threshold levels: 15-90%, with step 5%. 100% correspond to maximum volume the microphone and sound card are able to report, which is 1V in terms of analog voltage. Figure 8 shows the total number of potential potholes positions detected and the fraction which are

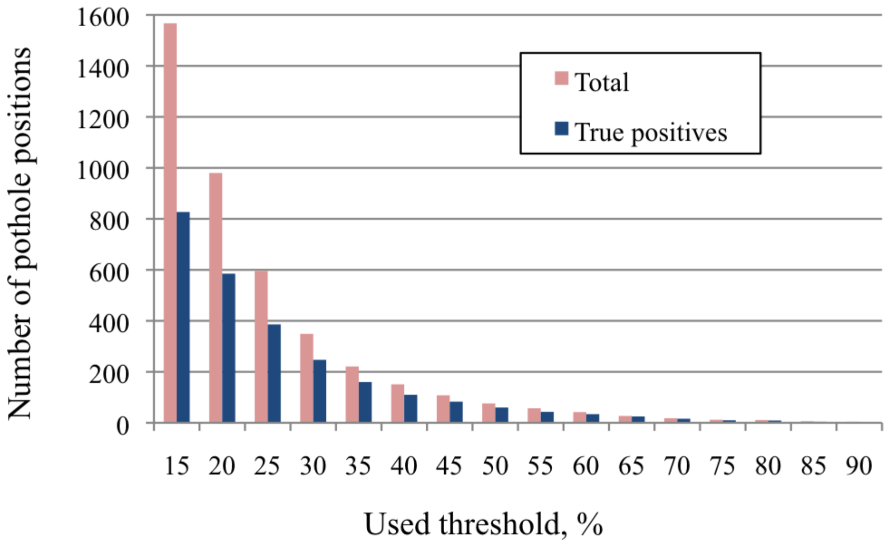

Fig. 8. Total detected positions and true positive count by each threshold, counted over all 10 test drives

treated as true positives by each threshold level. Thresholding with levels under 30% detect many potential potholes, levels over 65% - very few. It can be seen from Figure 9, that positions reported by low using thresholds are mostly noise, while thresholds 65% and above report 100% true positives but only a few, inferring. We conclude, that pothole detection from sound by thresholding can be divided into three intervals:

1. Noise (thresholds $\leq$ 30%): all vibrations, lot of noise
2. Sensitive (thresholds 35-60%): all potholes with moderate accuracy
3. Conservative (thresholds $\geq$ 60%): only the most remarkable potholes, but with high confidence

These particular threshold values are vehicle and microphone specific. Each participating car must perform a calibration before deployment. However we believe, that tendencies of three threshold intervals hold for other system configurations. The evaluation of this hypothesis is a future work. We have also performed proof-of-concept drives with different vehicles, including public transport bus driving along a 90km long route. But the additional sample set contains low number of test drives at the moment and is therefore not included in this paper.

Positions which did not have any ground truth pothole in 100m radius were treated as noise and discarded. Such erroneous positions were only encountered for threshold values under 35% and were less than 3% of total detected pothole positions.

We examined the distribution of distances between detected and ground truth positions, results are depicted in Figure 10. Results show, that thresholds 35-

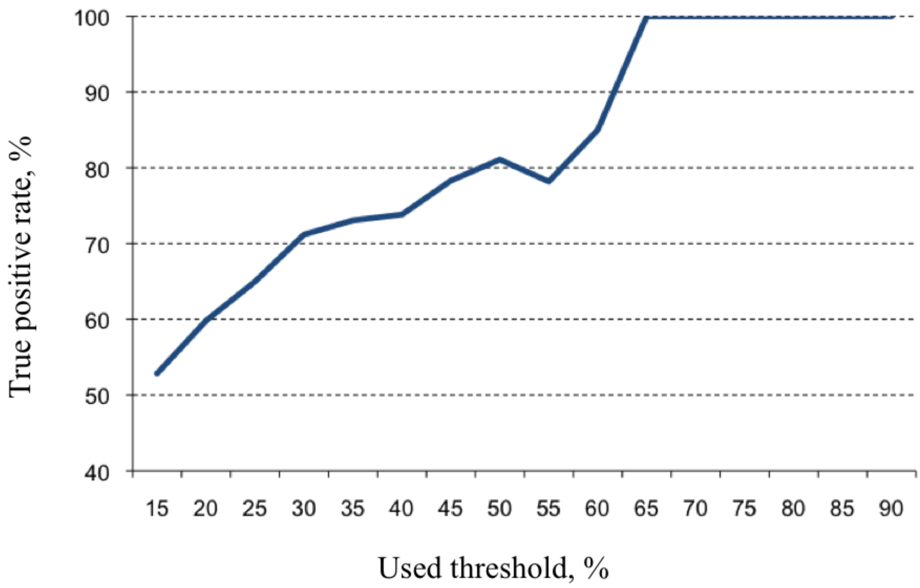

Fig. 9. True positive rate by each threshold. Thresholds above 60% give 100% true positives

60% give positions which are not further than 20m from a real pothole with more than 80% credibility. All the positions detected by thresholds above 60% are in range 0-10m - very high accuracy. But we have to note, that data sets in these cases contain only under 30 positions, which, in our opinion, is not sufficient to draw conclusions.

To assess what fraction of road irregularities marked as ground truth are detected by using recorded sound signal thresholding, we define an acknowledgement criterion: ground truth position is considered as acknowledged by our algorithm if it has at least 4 true positives in the total 10-drive test data set. Figure 11 shows the acknowledgement results. Not surprisingly, large potholes are most distinguishable because of the significant vibrations they cause. Small potholes do not fall far behind. Therefore we conclude that our approach detects potholes better than other types of road irregularities.

Drain pits are the least noticed category, which is a positive feature of our approach, as drain pits are not the type of rough we are most interested in. Also few gaps are recognized because their narrowness induce only moderate vibrations. The reason of imperfect cluster detection is mainly their size and ground truth marking methodology. We marked their approximate center. However, detected cluster position may vary, as their size exceeds 5m in most of the cases. It would be more correct if not only the center but also the size of each cluster would be stored.

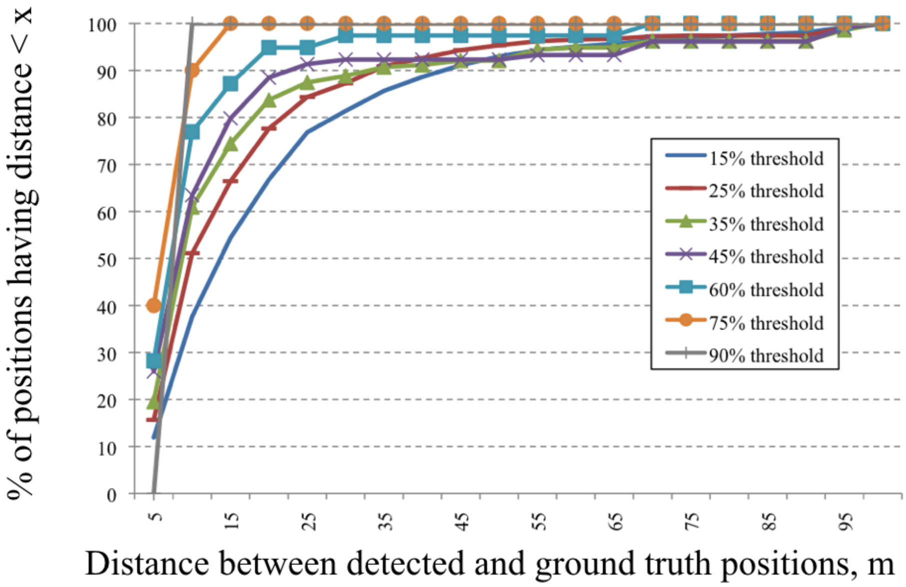

Fig. 10. Distribution function of distances between detected positions and ground truth, using thresholds 15-90%. Thresholds above 30% give $< 20m$ accuracy with $> 80\%$ credibility

4 Conclusion and Future Work

We have proposed a vehicular sensing system architecture that includes a regular PC computer, low cost sensors and a GPS receiver. The system was evaluated on a particular application - pothole detection using mobile microphones. The detection was performed by carefully selecting thresholds on the amplitude of the audio signal. We performed 10 test drives on a 4.4km long test route over public roads during a period when many potholes occur on the roads due to melting snow and ice. The experimental results were evaluated by the ground truth - manually marked road surface irregularities classified in five groups: large potholes, small potholes, pothole clusters, gaps and drain pits. The results show, that our method detects potholes on the road with more than 80% reliability and the detection accuracy depends on GPS capabilities and driving speed. By adjusting the threshold value we can either detect more potholes with less accuracy, or only the most remarkable ones with high confidence.

The future work includes evaluating the impact of using different vehicles and microphones and to improving the accuracy by using additional DSP methods and multi-modal sensors.

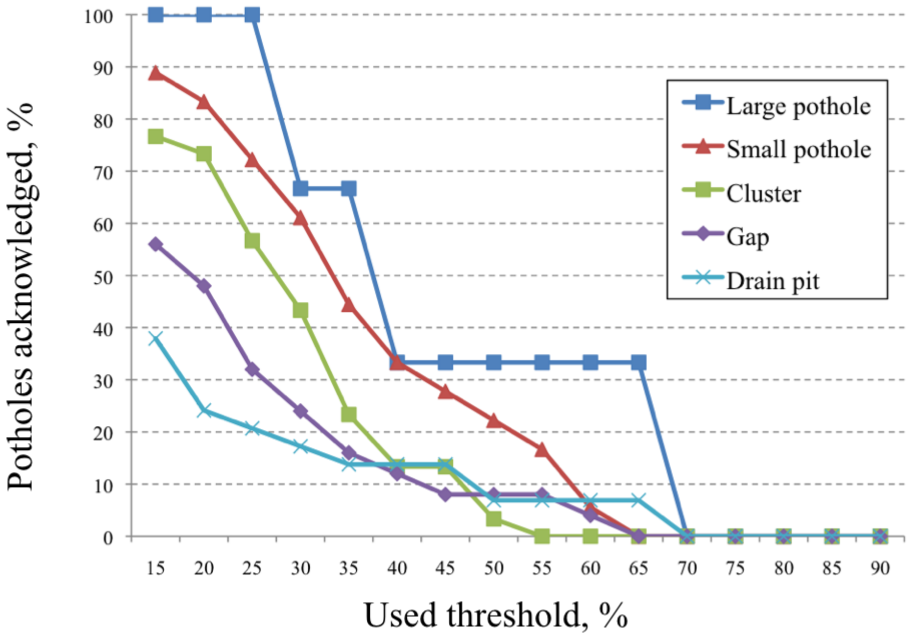

Fig. 11. Fraction of ground truth potholes acknowledged by our algorithm, using different thresholds for sound signal analysis

5 Acknowledgements

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