Applied Computer Science, vol. 19, no. 1, pp. 15–24
doi: 10.35784/acs-2023-02

Submitted: 2023-01-18 | Revised: 2023-02-28 | Accepted: 2023-03-06

Keywords: road quality, internet of things, edge processing

Marcin BADUROWICZ [0000-0003-2249-4219]*, *Sebastian ŁAGOWSKI***

USAGE OF IOT EDGE APPROACH FOR ROAD QUALITY ANALYSIS

Abstract

In the paper, the authors present the analysis of implementation of IoT system for road quality analysis. The proposed system was prepared for edge processing, on device. It allows to reduce the amount of data sent to cloud computing aggregation subsystem, sending only 2.5% of the original data. Several algorithms for road quality analysis were implemented on a real device and tested under real conditions. The system was compared with the state-of-the-art offline processing approach and showed the same accuracy on a set of known road artefacts, while detecting 92% of the artefacts recognized by the original cloud computing processing system.

1. INTRODUCTION

The number of cars and the size of the road network are steadily increasing, but it is very common for roads to be inadequately maintained, hence they deteriorate, resulting in a decrease of travel comfort. The report from 2022 published by General Direction of Roads and Motorways in Poland (GDDKiA) showed that at the end of 2020, 25.1% of roads were in the warning state, while 8.2% was marked as bad (Generalna Dyrekcja Dróg Krajowych i Autostrad, 2022). This is however only a part of the problem because the report lists only the major roads. Those which are maintained by the territorial government units are even worse, for example, as is shown in the report of Hrubieszów region (Powiatowy Zarząd Dróg w Hrubieszowie, 2022).

There would be an interesting solution to prepare the Internet of Things (IoT) system, where the user can provide information about road quality and access such information, for example to avoid roads which are in a bad state. More importantly, a low-cost embedded type of device can be used as a base for a continuous monitoring system improving maintenance interventions with the respect to the conditions and the overall maintenance budget.

The issue of finding the potential problems in the road surface, e.g. potholes or surface degradation points, as well as elements of the road which may cause the decrease of driver comfort, especially by using mobile devices and crowdsourcing is a problem being currently

* Lublin University of Technology, Faculty of Electrical Engineering and Computer Science, Department of Computer Science, Poland, m.badurowicz@pollub.pl
** Lublin University of Technology, Faculty of Electrical Engineering and Computer Science, Department of Computer Science, Poland, sebastian.lagowski@pollub.edu.pl

under serious work by many researchers in multiple countries, since at least 2008 (Mohan et al., 2008).

In this paper, the authors are willing to answer if there is a possibility to employ road artefact detection directly on the IoT acquisition device, thus limiting the amount of data being sent to the central processing system, if the already implemented algorithms are able to work in the streaming processing mode, and what will be their accuracy. The authors previously worked with similar systems, where all the processing was performed in the cloud computing system, using smartphones only as a data acquisition devices.

2. RELATED WORKS

The concept of using IoT systems to analyze the road condition by applying either cameras or accelerometers has been discussed with the major focus on smartphones (Astarita et al., 2012). The works range from simple thresholding (Nguyen et al., 2019), through different filtering methods (Mednis et al., 2011), dynamic time warping (Singh et al., 2017), usage of fuzzy methods (Badurowicz et al., 2020), and finally – Machine Learning approaches, especially based on Support Vector Machines (Vamsee et al., 2017), but also neural networks of various kinds (Gonzalez et al., 2017). Most of the proposed solutions are used online, sending the data to the global processing system (Astarita et al., 2012), where the analysis is being performed, thus treating a smartphone as a kind of IoT device.

The usage of smartphones is a good all-in-one package solution as the device is already equipped with required sensors (accelerometer, gyroscope), but also communication means (3G/4G modem) and some kind of user interface. However, this solution is more expensive than dedicated IoT-class device.

The concept of online processing system is problematic in one situation, namely when considering the amount of data being sent over the network to the processing system. For such systems, the frequency of data acquisition ranges from 10 Hz to 100 Hz, where each data packet includes information on acceleration, orientation, time and location (Badurowicz & Cieplak, 2019), so that the final data packet can reach 50 -100 bytes. In combination with high-frequency systems it creates a data stream of at least 1 KB per second, where the overhead of a protocol such as MQTT is not so high (Pérez et al., 2021). For commercial data plans, this is not a lot, but when the system lacks 4G connectivity and has to use other means (e.g., LoRa), this amount of data to transmit is too much. Similar situation is with 4G M2M (Machine to Machine) connectivity, which is also very expensive.

In an attempt to limit this and send only data about found road artefacts to the cloud system, some kind of processing can be implemented on the device. For example, a data packet can only be sent if the data stream is something resembling a road artefact pattern, but this requires processing directly on the IoT device, in what is known as "processing on the edge" fashion.

Hopefully, smartphones are powerful enough to take advantage of even neural network-based systems, while neglecting potential battery drain issues. However, everything changes when low-power devices are included. The authors (Badurowicz & Cieplak, 2019) previously discussed the concept of building a specialized low-power, low-cost device that could be attached to cars for crowdsourcing data analysis, in the form of devices built on ARM architecture. Such a concept has also been discussed by other authors (Loprencipe et al., 2021). Devices such as ESP8266 and its derivatives are popular and compelling when considering the "embedded" category, but they are not sufficient to implement ML models, even after significant trimming.

3. THE PROPOSED SOLUTION

3.1. The hardware side

Some of the algorithms which are discussed in this field, are currently taken into account to be implemented in streaming analytics fashion directly on the device, and are simple enough to be implemented on IoT embedded class devices. The authors decided to concentrate on ESP32, which is an embedded platform equipped with a dual-core XtensaLX6 processor at 240 MHz and 520 KB of RAM (ESP32 Series Datasheet, 2023), which has an integrated Wi-Fi and Bluetooth LE connectivity, still staying in the low-cost zone of about $10 and may be programmed with open-source development tools (Czerwinski & Przylucki, 2016).

This device, as the main processor, has been partnered with micro electromechanical Inertial Measurement Unit (IMU). It is a single chip multi-axis device that estimates linear accelerations and angular velocities, commonly by integrating accelerometer and gyroscope, often paired with magnetometer to perform conversion between local and global orientation systems. For the proposed system, the MPU-9250, a 9 degrees of freedom module has been used. The inertial module integrates the accelerometer and gyroscope (the inertial sensors), the magnetometer and a pressure module (barometer and thermometer) (Loprencipe et al., 2021). The readings are digitized using the on-chip 16-bit ADC (analog to digital converter) and published to the ESP32 device using the I^2C interface.

To mark the position of the potential classified road artefact, the user's physical position must be known. In order to achieve this, the NEO-6M-based GNSS (Global Navigation Satellite System) module has been used. It connects with the ESP32 device using the NMEA protocol over the UART (serial) communication interface. The developer states that positioning accuracy (kamami.co.uk, 2022) should be approximately 3 meters, which is adequate for a continuous road monitoring system, where workers should be sent to perform a maintenance at the final stage.

The devices was mounted on a breadboard and made into a small-factor form of the size of about 10x10 centimeters. The power source was a car-mounted phone charger.

3.2. The software side

Usual algorithms used for thresholding-based search for road artefacts are Z-THRESH, Z-DIFF, QSUM-THRESH and G-ZERO (Nguyen et al., 2019). The authors (Badurowicz et al., 2020) previously prepared a modified version of the Z-THRESH algorithm, the MOD-Z-THRESH, which improved the accuracy up to 93% while decreasing the False Positive Rate (FPR) down to about 5%. On the basis of the above, the authors decided to implement MOD-Z-THRESH, QSUM-THRESH and G-ZERO for the "edge processing" variant of the device. The basic approach was to acquire the values of acceleration in the Z2 axis, which is the calculated reoriented axis perpendicular to the Earth's surface, as well as to search for the values which are over a defined threshold.

In the case of MOD-Z-THRESH, the threshold is dynamically calculated based on the standard deviation of the last N values and a constant, M. In the case of this research, the M value of 4.3 has been decided, similarly to the previous approaches, while the N number was decided to be equal to 100.

In the case of QSUM-THRESH, the square root of the sum of squares of all (X, Y, Z) accelerations must be above a static threshold. The value of 1.2 has been decided, based on earlier experiments.

In the case of G-ZERO approach, the detection is marked when the values of all (X, Y, Z) acceleration are close to 0, which means the free fall of the measuring device.

All algorithms have been implemented using the C++ language and the Arduino framework and were working directly on the ESP32 device. For communication with the GPS module, the TinyGpsPlus library (Hart, 2022) has been used, while using (Kono, 2020) library for communication to the MPU device.

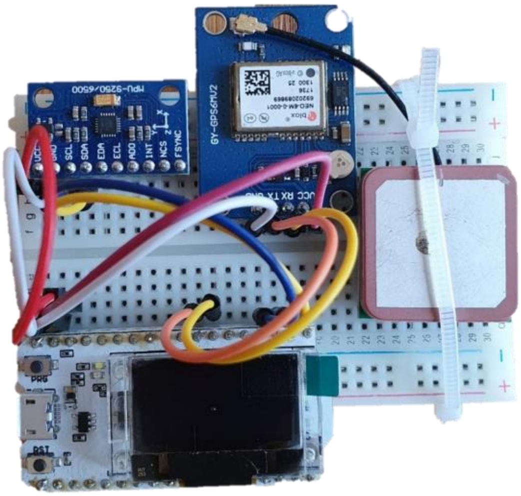

Fig. 1. The acquisition and processing device and its components

4. EXPERIMENTAL RESULTS

The experiment goal was to understand if the edge processing variants of the algorithms are able to detect and save positions of the road artefacts. The experiment was performed in Lublin, Poland, on a track of 15 km of length, through different types of streets varying with their quality, as presented in Figure 2. The device has been stably mounted in the test car, Peugeot 207 SW under the passenger's seat, to record vibrations measured as acceleration values when the car was driving over the different road artefacts.

The device was accompanied by a second test device, a Nokia Lumia 820 smartphone equipped with the previous implementation of the author's data acquisition software (Badurowicz et al., 2016), which will be used to cross-validate the results.

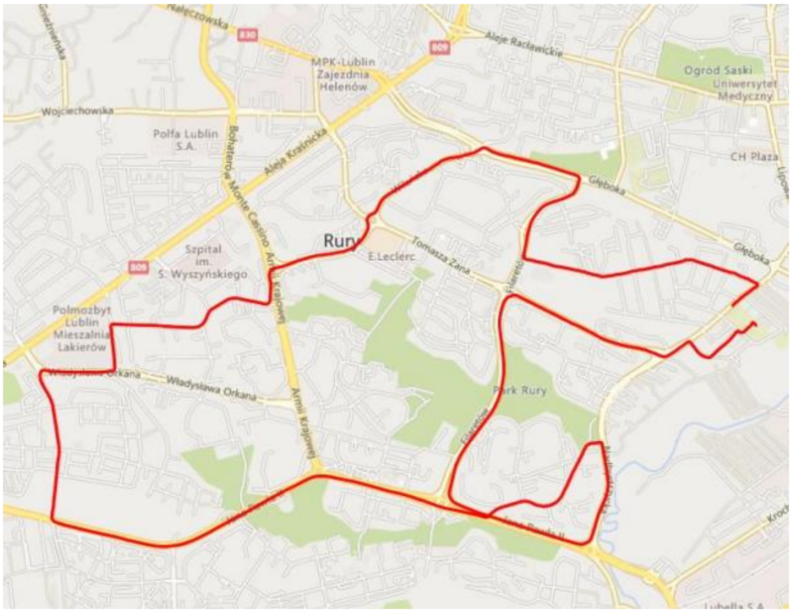

Fig. 2. The track of the experiment, as mapped on the map of Lublin, Poland (red)

The system was prepared in an offline manner. The device was performing streaming analytics with implemented algorithms and saving the results to the internal flash memory to be read after the experiment.

4.1. Known artefacts

The first phase of the experiment was to analyze if the Edge-processing variants of the implemented algorithms are able to perform proper classification. The experimental track included the locations of 19 known locations, consisting of 12 speed bumps and 7 potholes. In the case of both MOD-Z-THRESH and QSUM-THRESH, all the known artefacts were detected by the system. In the Figure 3, where the positions of the known artefacts were marked with red pins, the fragment of the test track is presented, while the green circles are the positions of artefacts as detected by the MOD-Z-THRESH algorithm.

The G-ZERO approach has not found any of the known artefacts; thus its results have been ditched in the following phases of the experiment.

The important point is that, however, due to potential inaccuracy of the GNSS system, the classification was marked as positive if the location of the detected road artefact were in a circle of 10-meter radius of the known position of the road artefact. A value of 10 meters is based on the previous research (Badurowicz & Cieplak, 2019) and the approximate average value of reported smartphone-based GNSS system accuracy.

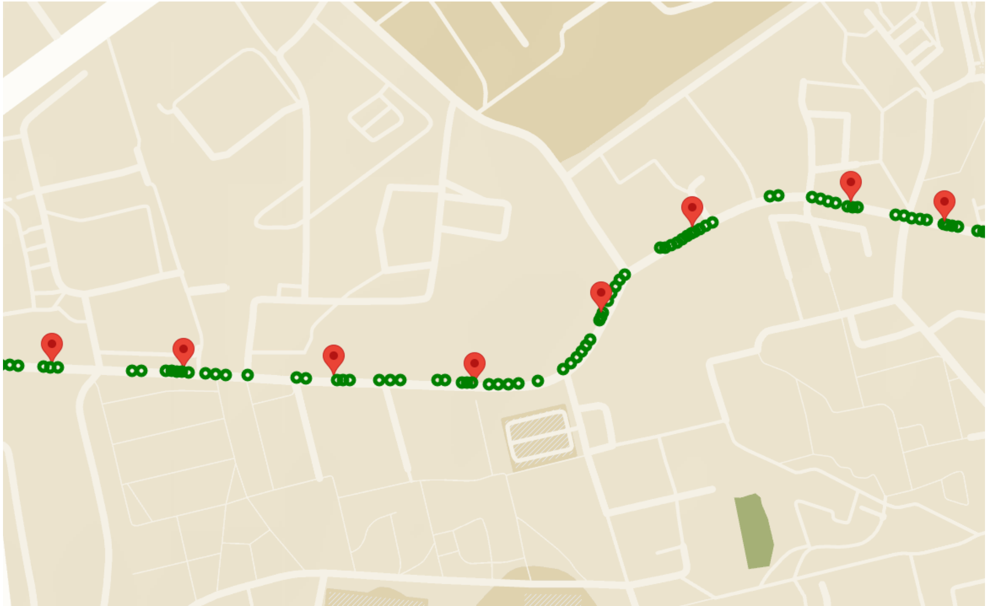

Fig. 3. Locations of the detected road artefacts (green) and known artefacts (red pins)

4.2. Aggregation process and visualization

The second problem is that even if a single road artifact is found, it can sometimes happen that this particular artefact can be detected multiple times. This issue was analyzed by the authors and can be seen in Figure 4 and also in Figure 3.

In the case of the elevated pedestrian crossing presented in Figure 4, the algorithms are detecting both coming "up" and "down" the crossing – the "known" position is marked by a red circle, while the detections by smaller green circles.

In the previous works, this was solved by aggregation – grouping together detections which are in close proximity to each other. A similar process was used in this experiment, where points were aggregated to a radius of 2 times the current GNSS system accuracy, as reported by the GNSS device itself.

Finally, the two Edge variants of the algorithms, MOD-Z-THRESH and QSUM-THRESH detected 557 and 267 road artefacts in total.

When cross-validated against the previous implementations, the non-Edge variant of MOD-Z-THRESH detected 372 road artefacts when analyzing the data from the smartphone on the same road fragment, and 92.31% of detections were included in the detections from the Edge-processing variant.

Finally, for cross-validation of the results, the geographical locations of the detected road artefacts have been plotted onto a satellite images of a resolution ranging from 10 to 15 centimeters per pixel, as presented in Figure 5 and 6. Such images were used as a basis for a manual checkout where the authors visited the marked locations and visually confirmed the potholes (the three presented in Figure 5) and asphalt discontinuity (Figure 6). Thus, the satellite image may be a useful asset when presenting the road artefact report to the road operator or road work crew.

Fig. 4. Locations of the known road artefacts (red) and detected artefacts (green)

4.3. Data transfer limitation

The final amount of data, consisting only of locations of the detected road artefacts, current date and time, classification values and GNSS system local accuracy, for detected 557 artefacts, measured only 194 bytes per single artefact and 108,058 bytes in total. The measurement of raw data amounted to 4,183,538 bytes, so the data volume to be transmitted to the central processing system was only 2.5% of the original, making it more accessible to sending over the M2M (Machine to Machine) GSM systems.

During the experimental phase, the authors also calculated the average horizontal dilution of position (HDOP) as reported by the GNSS device, which was 1.068. This result is roughly calculated to be equal to 4.27 meters based on the device manufacturer's specification.

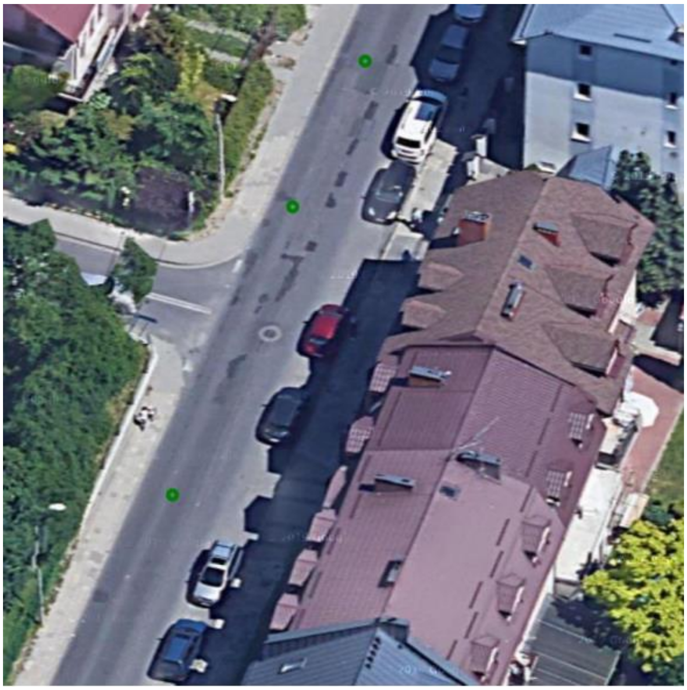

Fig. 5. Locations of the detected road artefacts (green) on a satellite imagery

Fig. 6. Locations of the detected road artefacts (green) on a satellite imagery

5. SUMMARY AND CONCLUSIONS

The experiment confirmed that Edge variants of the algorithms are able to detect as many road artefacts as their non-Edge variants, thus making the implementation of the algorithms directly on the IoT device possible.

The system is not perfect. For the time being, the presented solution used three algorithms already in use, with a low acquisition frequency. The higher frequency must be analyzed in the further experiments. The data that is saved as a result of Edge processing is also a limitation. In the presented research, the authors were saving only the final positions of the found road artefacts. However, in a real implementation, it is worth saving and transferring through the network the pure acceleration values of the road fragment where the artefacts were detected, in order to use the Edge processing as a first filter before applying more advanced algorithms in the cloud computing system.

In the next phase of experiments, the authors want to implement the presented IoT solution to a new problem, which is the measurement of passenger comfort while cycling. While detection of road artefacts by car drivers is an interesting solution, the smartphone is quite useful in the car for other purposes. However, in case of bike, the usage of the small and cheap IoT device could be more useful, as it could be mounted without thinking about losing an expensive smartphone device.

REFERENCES

Astarita, V., Caruso, M. V., Danieli, G., Festa, D. C., Giofrè, V. P., Iuele, T., & Vaiana, R. (2012). A mobile application for road surface quality control: UNIquALroad. *Procedia - Social and Behavioral Sciences, 54*, 1135–1144. https://doi.org/10.1016/j.sbspro.2012.09.828

Badurowicz, M., & Cieplak, T. (2019). Real-time road quality assessment using smartphones and cloud lambda architecture. *MATEC Web of Conferences, 252*, 03011. https://doi.org/10.1051/matecconf/201925203011

Badurowicz, M., Cieplak, T., & Montusiewicz, J. (2016). The cloud computing stream analysis system for road artefacts detection. In P. Gaj, A. Kwiecień & P. Stera (Eds.), *Computer Networks: 23rd International Conference, Proceedings* (pp. 360–369). Springer International Publishing. https://doi.org/10.1007/978-3-319-39207-3_31

Badurowicz, M., Montusiewicz, J., & Karczmarek, P. (2020). Detection of road artefacts using fuzzy adaptive thresholding. *2020 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)* (pp.1–8). IEEE. https://doi.org/10.1109/FUZZ48607.2020.9177822

Czerwinski, D., & Przylucki, S. (2016). Open-source microcontroller development board in wireless sensor networks classes. *ICERI2016 Proceedings, 1*, 2294–2300. https://doi.org/10.21125/iceri.2016.1504

ESP32 Series Datasheet. (2023). *Espressif Systems (Shanghal)* https://www.espressif.com/sites/default/files/documentation/esp32_datasheet_en.pdf

Generalna Dyrekcja Dróg Krajowych i Autostrad. (2022). *Raport o stanie technicznym nawierzchni sieci dróg krajowych na koniec 2021 roku*. https://www.gov.pl/web/gddkia/raport-o-stanie-technicznym-nawierzchni-sieci-drog-krajowych-na-koniec-2021-roku

Gonzalez, L. C., Moreno, R.., Escalante, H. J., Martinez, F., & Carlos, M. R. (2017). Learning roadway surface disruption patterns using the bag of words representation. *IEEE Transactions on Intelligent Transportation Systems* (pp. 1–13). IEEE. https://doi.org/10.1109/TITS.2017.2662483

Hart, M. (2022). *TinyGPSPlus*. https://github.com/mikalhart/TinyGPSPluskamami.pl. (2022). *GY-GPS6MV2*. https://kamami.pl/gps/563067-gy-gps6mv2-modul-gps-z-ukladem-u-blox-neo-6m.html

Kono, A. (2020). *MPU9250_asukiaaa*. https://github.com/asukiaaa/MPU9250_asukiaaa

Loprencipe, G., de Almeida Filho, F. G. V., de Oliveira, R. H., & Bruno, S. (2021). Validation of a low-cost pavement monitoring inertial-based system for urban road networks. *Sensors, 21*(9), 3127. https://doi.org/10.3390/s21093127

Mednis, A., Strazdins, G., Zviedris, R., Kanonirs, G., & Selavo, L. (2011). Real time pothole detection using android smartphones with accelerometers. *2011 International Conference on Distributed Computing in Sensor Systems and Workshops, DCOSS'11* (pp. 1-6). IEEE. https://doi.org/10.1109/DCOSS.2011.5982206

Mohan, P., Padmanabhan, V. N., & Ramjee, R. (2008). TrafficSense : Rich monitoring of road and traffic conditions using mobile smartphones. *In The 6th ACM Conference on Embedded Networked Sensor Systems* (pp. 1–29). The ACM Digital Library. https://doi.org/MSR-TR-2008-59

Nguyen, V. K., Renault, É., & Ha, V. H. (2019). Road anomaly detection using smartphone: a brief analysis. *Mobile, Secure, and Programmable Networking. MSPN 2018. Lecture Notes in Computer Science* (vol. 11005). Springer. https://doi.org/10.1007/978-3-030-03101-5_8

Pérez, E., Araiza, J. C., Pozos, D., Bonilla, E., Hernández, J. C., & Cortes, J. A. (2021). Application for functionality and registration in the cloud of a microcontroller development board for IoT in AWS. *Applied Computer Science*, *17*(2), 14–27. https://doi.org/10.23743/acs-2021-10

Powiatowy Zarząd Dróg w Hrubieszowie. (2022). *Ocena stanu technicznego dróg powiatowych powiatu hrubieszowskiego*. https://www.starostwo.hrubieszow.pl/dat/attach/2022-04/31923_ad-10-ocena-stanu-technicznego-2021.pdf

Singh, G., Bansal, D., Sofat, S., & Aggarwal, N. (2017). Smart patrolling: An efficient road surface monitoring using smartphone sensors and crowdsourcing. *Pervasive and Mobile Computing*, *40*, 71–88. https://doi.org/10.1016/j.pmcj.2017.06.002

Vamsee, K. K. M., Vimalkumar, K., Vinodhini, R. E., & Archanaa, R. (2017). An early detection-warning system to identify speed breakers and bumpy roads using sensors in smartphones. *International Journal of Electrical and Computer Engineering*, *7*(3), 1377–1384. https://doi.org/10.11591/ijece.v7i3.pp1377-1384