

Survey on Pothole Detection Methods

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Abstract—Transportation services for safe travel are critical to a country's growth. The dangerous pavement surface is caused by a variety of asphalt pavement distresses. Potholes are the primary cause of pavement distress. Many methods for detecting and correcting potholes in asphalt pavement have been presented in this paper. Potholes are essential indicators of structural difficulties in the asphalt road, and recognition of the potholes is a significant issue for smooth and safe driving. On the other hand, manually discovering and evaluating strategies is expensive and time-consuming. Consequently, several efforts have been made to develop technology for the detection and recognition of potholes automatically, which may reduce vehicle damage, driver stress with a smaller number of accidents. In this review paper, we explored and reviewed the existing pothole detection systems based on sensor, vision, machine learning, and deep learning algorithms. The systems based on equipment and methods are presented in this paper.

Index Terms— Computer vision, Deep learning, Machine learning, Pothole detection, sensor.

I. INTRODUCTION

Traffic congestion has been increasing in India as a result of economic growth and a rapid increase in the number of vehicles. The number of accidents is exponentially increasing due to poor road conditions. As per the record of the ministry of road transport and safety in 2019, 1,54,732 people were killed due to road accidents. According to studies, ten to twenty percent of road accidents are caused by drivers who are not paying attention. Due to prolonged driving, the driver will not be able to focus on the road, which will result in an accident. When the vehicle collided with the pothole, it suffered damage such as a flat tyre, bent or broken rims, suspension damage, steering damage, and even body damage. Because the potholes are water/mud-filled during the monsoon, determining the depth of the pothole is difficult. Recently, the potholes on the road increase due to environmental changes, such as heavy rains and snow. As a result, pothole-related accident complaints and lawsuits are on the rise. A pothole is bowl shape deformity present on the pavement surface with a minimum circumference of 150 mm [1].

As the world's second-most populous country, India consumes a complicated network of streets. In India, streets are the primary means of transportation, carrying 90% of all traveler traffic and around 65% of all freight [2]. However, most of India's streets are congested and narrow with low quality. In the previous two decades, the number of automobiles on the road has expanded substantially. This increase in the number of vehicles has caused concerns such as traffic congestion during rush hour and multiple accidents on the road, with the primary cause being the poor quality of the roads. Potholes produced by severe rains, an ill-conceived drainage system in urban areas, and the passage of large automobiles all play a role in the increased likelihood of disasters and

human deaths. According to the Ministry of Road Transport and Highways' assessment report "Road Accidents in India, 2017," a total of 1.47 lakh people have died due to road accidents. According to the new numbers from a few state governments, potholes claimed the lives of 3,597 people across the country in 2017, an increase of more than half from the previous year. Every day, almost 30 people die on the streets due to potholes [2]. Figure 1 displays the situation of dangerous potholes on city streets. Drivers have avoided accidents caused by potholes due to the many pothole detection methods proposed.



Figure 1. Potholes on the road

II. STATE OF ART METHODS FOR POTHOLE DETECTION

Some of the techniques for detecting potholes are listed below.

A. Sensor-Based Pothole Detection

Yu et al. [3] proposed developing a vibration-based method for the assessment of pavement situations using current data-collecting technology. Due to pavement distress, the vehicle is subjected to impact forces, such as cracks and rutting. The system has the advantages of low storage requirements, low cost, and the ability to analyze data automatically in real-time. However, unlike a video-based system, it does not reveal all subtleties of distress symptoms. The vehicle's service condition, such as tyre pressure, should also be standardized to compare findings. The system can be accelerated by adding accelerating sensor boards. De Zoysa et al. [4] built a sensor network based on the bus transportation system to monitor road surface structure (BusNet). busnet is a sensor network that analyses environmental toxins using sensors installed on public transit vehicles.

Erikson et al. [5] looked into how mobile sensing could identify and report road surface conditions. They developed the "Pothole Patrol" system, which collects data from three-axis acceleration sensors and GPS devices in automobiles. Using a basic Machine Learning (ML) approach, they used accelerometer data to identify potholes and other substantial road surface irregularities. They also used opportunist WiFi connections given by membership in the open WiFi access points service to submit detection methods to central servers. Accelerometers are unable to detect potholes in the middle of a lane. In contrast, potholes in the road joints or repair holes can be detected as potholes using vibration-based approaches.

Accelerometers are used in the vibration-based approach to detect potholes. These approaches require less storage and can be employed in real-time processing, which is one of the benefits of a vibration-based system. However, vibration-based approaches may produce inaccurate results, such as misclassifying road hinges and joints as potholes, and in the middle of a lane can't be identified using accelerometers since none of the vehicle's wheels hit them [5]. Mednis et al. [6] suggested an Android-based smartphone-based mobile sensing system for detecting road irregularities. The chosen test track is 4.4 kilometers long, and the test drive session consisted of ten laps in a row. The technology used for the test-driving session includes a BMW323 touring passenger car and cellphones. The assessment of chosen data processing algorithms using real-world data shows a true positive rate of up to 90%.

Faith Orhan et al. [7] presents a work made using the android platform to recognize traffic dangers. This system has sensing, analyzing and sharing components. The first sensing component collects the data of accelerometer and send to the GUI. This data can be used for the analysis. Third component i.e., sharing, which plays the role of communication. All obtained data is stored in a central repository for subsequent processing even though this technology informs fellow drivers about traffic occurrences. The cost and complexity of implementation rise. Using smartphone sensors, H. Agrawal et al. [8] offer a technique for identifying potholes on the road surface. This system developed android application which collects the data from an accelerometer and gyroscope and stored in the database. It can then be handed over to the proper authorities for road maintenance.

The design of a pothole detecting sensor by Hadistian Muhammad Hanif et al [9] was inspired by the proximity sensor system, which uses a camera and a digital image approach. Our technology, which we study and develop, has the advantages of being more user-friendly in terms of feasibility and cost. As a result of this study and examination, an error in the distance between the pothole and the sensor was observed be less than 4%. Table 1 presents a review of the sensor-based pothole detection methods.

TABLE I. SENSOR BASED POTHOLE DETECTION METHODS

Authors	Methods	Equipment & experiments
Yu and Yu [3]	Using acceleration records	• ICP accelerometer, PC oscilloscope
De Zoysa et al. [4]	Using acceleration and BusNet	• Acceleration sensor
Erikson et al. [5]	Using accelerometer data	• GPS devices and three-axis acceleration sensors.
Mednis et al. [6]	Using accelerometer sensor of smartphone	• Android OS-based smartphones • Test drive in Riga, Latvia
Faith Orhan et al. [7]	Sensing, Analysis, and Sharing	• Accelerometer
H. Agrawal et al. [8]	Using accelerometer and gyroscope	• Accelerometer sensor • Gyroscope sensor
Hanif et al [9]	Sensor-based and digital image-based system	• proximity sensor • camera

B. Computer Vision-based approach

There are three types of computer vision-based pothole detection methods. 1) 2D Image-Based Approach 2) Video Based Approach 3) Stereo based Approach

2D Image-based approaches

The geometry of a pothole can be approximated using the graphic properties of a faulted zone. Suppose a pothole is determined to have a coarser and grainier composition than the ROI. In that case, the region's composition is obtained and related to the composition of a faulty region.

To investigate 3D pavement distress images, Moazzam et al. [1] suggested an economic model. By adopting a low-cost Kinetic sensor that gives immediate depth measurement, the calculation cost is lowered. The sensor is made up of an IR and RGB camera that takes depth images and RGB images, then processed in a MATLAB environment to identify the depth of potholes by obtaining metrological and unique data. Koch and Brilakis [10] described a technique for detecting potholes in asphalt pavement images that were automated. In this approach, first, the defective area is segmented. After that, the geometric attributes of a fault zone are employed to estimate the shape of a potential pothole. A pothole is defined as a defect zone with a rougher and blurrier texture than the surrounding surface texture. A total of 120 images were acquired, with 50 being used for training and the rest for testing. With a precision of 82% and a recall of 86%, the accuracy was 86%.

Buza et al. [11] have created a novel unsupervised vision-based technique that requires no costly equipment, further filtering, or training. To find and estimate potholes, they use image processing and spectral clustering. Image segmentation, geometry extraction using spectral clustering, identification, and extraction are all included in the proposed technique. The suggested approach was created in MATLAB and tested using 50 Google image library pothole images. Estimating the surface area of a pothole had an accuracy of roughly 81%.

Ryu S-K et al. [12] proposes a pothole identification approach that makes use of multiple aspects in 2D images to improve the previous method of pothole detection. The suggested technique consists of three steps: segmentation, extraction of candidate regions, and decision. The approach extracts dark patches for pothole identification using a histogram and the closure operation of a morphological filter. Then, using criteria like size and compactness, potential portions of a pothole are extracted. Finally, a comparison of potholes and background properties is used to determine if candidate regions are potholes.

Video-based approaches

A method for recognizing potholes, cracks, and patches from video recordings is presented by Lokeshwor et al. [13]. Using the Distributed File System (DFS) algorithm, the video clips are certainly segmented into two categories: stressed and distressed. The Critical Distress Detection, Measurement, and Classification (CDDMC) algorithm are used to process the distress frames database. For potholes, cracks, and patches, decision logic uses three visual features. Standard deviation, circularity, and average width are the three. The two-dimensional image-based method identifies potholes from a single frame; however, it is unable to discover pothole repercussions. Another approach proposed by Koch and Brilakis [14] is insufficient for single frames and

doesn't detect the extent of potholes using video-based pavement evaluation frames. This system uses vision tracking to track discovered potholes across all frames and provides a pothole detection approach with an updated configuration signature for perfect pavement zones.

Kang and Choi [15] used a 2D LiDAR and a camera to identify potholes. A combination of heterogeneous sensor frameworks was used to improve pothole detection accuracy. They also used an image processing-based pothole recognition method to improve the recognition accuracy. The rate of errors determines the success of their suggested process. Their proposed technique has a low error rate of roughly 0.02%, according to their test results. Li et al. [16] offer a pothole detection framework based on a sound system vision paradigm. Two USB cameras are used in the framework to take images simultaneously. To create the divergence map, they used the camera's acquired boundaries in conjunction with a checkerboard. A pothole district was identified by focusing all attention on the street surface model.

Jo Y. et al. [17] proposed a pothole identification method that leverages motion and feature intensity to reliably discriminate potholes from similar objects. In the suggested technique, the motion feature is the key source of data, providing comprehensive and noise-tolerant data for the segmentation of potholes from the environment. The suggested algorithm is substantially simpler than the authors' prior technique, consisting of two phases of segmentation and classification. The suggested approach beats existing pothole detecting techniques as well as the algorithm from the prior work, according to experimental data.

Stereo-based approaches

Wang [18] conducted a feasibility study to use stereovision technology to undertake a detailed survey of pavement conditions. To detect and characterize any cracks, the initial step is to analyze 2D images from each of the two cameras. The findings of assessing two picture sources of the same pavement are integrated, potentially improving accuracy by counting cracks overlooked by one analysis. Geometric modeling is also used to construct a 3D surface model with longitudinal and transverse features from two images taken on the same pavement surface. A series of processes should be followed to recover 3D attributes from a pair of 2D images taken on the same pavement surface, including camera calibration, distortion correction, stereo point matching, 3D reconstruction, and profile report. Hou et al. [19] presented a method for reconstructing the 3D pavement surface from a pair of photographs utilizing pavement imaging and stereovision. To photograph the road surface, four cameras were set in two pairs across a 4-meter-wide pavement. The four steps in this technique are calibration, distortion compensation, matching, and 3D reconstruction. In a stationary environment, 3D reconstruction resolution can only be 2mm, but in a dynamic moving environment, it may be more than 5mm.

Staniek [20] proposed using stereo vision methods for measuring pavement conditions and recording road network conditions with a stereo vision device attached to a car. This article contains a complete discussion of the suggested solution. The road segment was evaluated on a 650m local road as a field experiment. Recreating pavement surfaces using stereo vision algorithms requires a significant amount of computational effort to match feature points across two views. It isn't easy to employ them in a real-time setting. A unique stereo vision-based pothole identification system is suggested by Bangalore Ramaiah et al. [21], which identifies potholes and accurately determines their depth. The presented method uses an intensity and disparity image derived from a pair of stereo images to pick a region of interest (ROI) of possible pothole candidates. Finally, the suspension system's damping coefficient is controlled using 3D data from detected potholes to improve ride quality. The suggested pothole detecting system has an accuracy of roughly 84% and can identify potholes up to 5 cm deep, according to experimental data. Furthermore, in-vehicle tests show that using the pothole detecting technology can enhance ride quality by roughly 16%. The suggested method may be used in commercial vehicles in real-time and might give considerable improvements in terms of safety and ride quality.

Table II presents review of the Computer Vision-based methods for detecting potholes.

C. Artificial Intelligence-based approach

ML-based approaches

Anaiss et al. [22] presented a Virtual Roadway Network Auditor (VRNI), which continuously monitors highway circumstances and assists directors and specialists in making decisions. The VRNI monitor employs a one-of-a-kind road impairment detection approach based on vertical and sidelong speed development data and two customizable one-class Support Vector Machine (SVM) models. Using data from a tiny school transportation arrangement in Australia's New South Wales, they tested their method. According to their study, their presented technique distinguishes 97.5% of road impairment from a 4% false warning that identifies with reasonable abnormalities such as development junctions. Using the Internet of Things, Bansal et al. [23] propose DeepBus, a mechanism for continuous identification of surface irregularities on roadways (IoT). The suggested method

TABLE II. COMPUTER VISION BASED POTHOLE DETECTION METHODS

Authors	Methods	Equipment & experiments
Moazzam [1]	low-cost Kinetic sensor	IR camera and an RGB camera
Koch and Brilakis [10]	2D image Based approach	- HP Elite Autofocus webcam used. - Tested 120 images with 640X480 resolution
Buza et al. [11]	2D image Based approach	50 Google image library pothole images
Ryu S-K et al. [12]	2D image Based approach	Extracts dark patches for pothole identification using a histogram and the closure operation of a morphological filter
Lokeshwor et al. [13]	Video-based approach	ARRB NSV produced 1275 video frames, including 283 grayscale images of resolution 1280*960 and 992 video frames of resolution 640*480.
Koch and Brilakis [14]	Video-based approach	- Used HP Elite Autofocus webcam. - Used 39 video frames of size 640X480 with 30fps.
Kang and Choi [15]	Video-based approach	- Used 2D LiDAR and Camera - The lower error rate of about 0.02%.
Li et.al. [16]	Video-based approach	- Used USB cameras - Focuses underneath the street surface model
Jo Y. et al. [17]	Video-based approach	- Motion feature - Intensity-based classification
Wang [18]	Using stereo vision	- Two cameras - Feasibility study
Hou et al. [19]	Using stereo vision	- Data Vehicle for the Digital Highway - Preliminary test
Staniek [20]	Using stereo vision	- Used two cameras test bench. - Test drive in Poland
]Bangalore Ramaiah et al.[21]	Using stereo vision	- Stereo camera - Depth based classifier

employs IoT sensors to detect potholes systematically. On a midway-aided map, the location of these potholes would be visible. The experimentation uses different ML algorithms such as SVM, KNN, Naive Bayes, Decision Tree, Ensemble Voting, and Random Forest. This system determined that the random forest algorithm achieved the greatest accuracy of 86.8%.

Deep learning-based approaches

Biju E.D. et al. [24] proposed the app "Unseen Abyss" which is used in this project to display the pothole's locations. The Raspberry Pi platform is used to identify potholes in this system. In this system, the raspberry pi camera is utilized to create a dataset. Train dataset is used to train the TensorFlow framework for pothole detection. The detected location of the pothole is stored in the google sheet. These coordinates are displayed to the end-user via an app created using Flutter. Aparna et al. [25] proposed using a CNN to identify potholes using infrared imaging. By altering specific settings twice, the authors reached test accuracy of 64.42% and 73.06% when compared to results from a self-built CNN architecture. The researchers also evaluated various pre-trained ResNet models. The authors attained validation accuracy of 97.08% through the ResNet101 pre-trained model on image size 224.

S. Hyunwoo et al. [26] suggested a method for detecting potholes with a smartphone and classifying them using transfer learning. 70% of the data is utilized for training, whereas 30% of the data among 100 samples are used for testing. This method accurately identified all occurrences, with a classification rate of 100%. In a group detecting-based application context, Varona et al. [27] suggested a DL (DL) method to identify the many sorts of street facets and identify potholes from disruptions given by vehicle behaviors. They look into and use a variety of DL models, including CNNs, LSTM algorithms, and repository calculation models. Their research was carried out with actual data, and the results revealed a good precision in addressing the two issues. CNN has a 98% accuracy rate, while Last Short-Term Memory has a 78% accuracy rate.

Surekha Arjapure et al. [28] proposed a Mask Region-Based CNN DL technique to precisely detect and segment potholes. Also, this technique helps to predict and calculate the area of detected potholes. The 291 images in the collection were painstakingly gathered by capturing local roads in Mumbai and surrounding motorways. VGG Image Annotator manual tool was used for dataset annotation. Using the proposed method, potholes are detected as an ROI from main images, and the area of the pothole is calculated based on ROI. The calculated area is

compared with the measured area to check the accuracy of the proposed method. The testing outcomes show that the recommended approach delivers an accuracy of 90% when comparing the calculated area of the pothole to the actual measured area with a 10% variance.

The DL strategy for pothole identification is discussed by J. Javier Yebes et al. [29]. They compiled a big database of pothole images. The dataset included images taken with various cameras, vehicles, and perspectives under various environmental circumstances, as well as images captured with various cameras, vehicles, and viewpoints. Four alternative deep neural network-based object identification models have been fine-tuned. R-CNN is now faster. Resnet101 achieved an average accuracy of 82%, whereas Faster RCNN Inception v2 achieved 75% at a reduced processing cost. The model is run at 5–6 frames per second using the Nvidia DrivePX2 platform. As part of the AUTOPILOT H2020 project, the pothole detector was tested in actual automobiles. Because potholes will be communicated to the IoT platform after identification and will act as a road danger alert, this detector's current frame rate is valid for autopilot. Immediate reactive vehicle maneuvers were not targeted. Also, the detector was unable to label the potholes and some road cracks on highly damaged road surfaces. More False positives due to manholes. Also, algorithms have limitations in high-speed driving. For fine-tuning of this algorithm, a larger dataset is required and can be used YOLOv3 for better accuracy.

Abhishek Kumar et al. [30] focus on a DL-based model that uses images and videos to detect potholes on the road early. DL methods including Transfer Learning, Faster RCNN, and Inception-V2 were employed in this model. A proposed model identifies potholes in images/videos in real-time and alerts the driver to the pothole in front of the vehicle. The experimental results show that the model gives extremely good results. In the future scope, this model can also be able to detect the location of potholes and update it on the map which will help other users get the alert about potholes from the app. Also, we can implement CNN in this model for achieving better detection accuracy. J. Dharneeshkar et al. [31], In India Road maintenance is a challenging task. Accident rates are increasing year by year due to potholes. So, it's necessary to provide a cost-effective automated process for detection. On Indian roadways, a new 1500-point dataset was developed. The YOLO algorithm is used to annotate and train the dataset. YOLOv3, YOLOv2, and YOLOv3-tiny were used to train the new dataset. The model had given reasonable accuracy. The model may be implemented in real-time utilizing the Raspberry Pi and the camera. The system can also be equipped with a GPS to track its whereabouts.

Ravi Agrawal et al. [32] present CNN model is used for pothole detection. The algorithm collects images of the road and categorizes it as Asphalt, Paved, or Unpaved, as well as detecting any potholes present in the image. This approach was also used to create an app that warns pedestrians about nearby potholes to prevent accidents. The model obtained a pothole identification accuracy of 88% and a road type classification accuracy of 96%. If images are labeled as filled or unfilled potholes, the model may be enhanced even further. Deep learning-based CNN has been suggested by G. B. R et al. [33] for recognizing potholes and humps on the road. A global positioning system (GPS) was used to determine the location of the pothole and send the information to the control center. Two more benchmark approaches, namely Kirchhoff's theory and K Nearest Neighbor (KNN), are chosen to validate the performance of the suggested method for predicting potholes on the road. The findings of the experiment reveal that the CNN-DL is superior to other approaches for identifying any type of road pothole. Table 3 presents the review of ML-based methods for detecting potholes.

Table III presents review of ML-based methods for detecting potholes.

III. DISCUSSION

We studied the existing pothole detection technologies, which are grouped into three categories: sensor-based methods, vision-based methods, and AI-based methods. The following are some of my observations.

- A sensor-based system will not be able to detect potholes early enough.
- Vision-based systems are intelligent, fast, and dependable.
- As a result, a pothole recognition approach based on multiple features in 2D images is required to improve the present pothole detection technique and precisely recognize a pothole.
- AI-based pothole systems are more precise, requiring more data and processing power.
- The pothole detection technology opens up a world of possibilities for research.

The following are the primary issues that will be addressed in the future,

- One of the newest and most popular technologies for locating potholes on roads is pothole detection. Prediction is synonymous with inaccuracy. As a result, the algorithm's ability to anticipate pothole density can be improved, resulting in more accurate predictions.
- In the case of sensor-based detection, the placement of the sensors has a significant disadvantage due to their range difficulties. This can be overcome by extending the sensor range.

TABLE III. ML BASED POTHOLE DETECTION METHODS

Authors	Methods	Equipment & experiments
Anaiss et.al. [22]	one-class SVM	Accuracy of 97.5% for the road vandalization of 4% bogus caution rate
Bansal et al. [23]	SVM, Logistic Regression, KNN, Decision Tree, Naive Bayes, Ensemble Voting, and RF.	The accuracy of Random Forest is the best model accuracy at 86.8%.
Biju E.D. et al. [24]	CNN	-
Aparna et al. [25]	self-built CNN, ResNet101	- Self-built CNN = 64.42% - ResNet101 = 73.06%.
S. Hyun woo et al. [26]	Transfer Learning	100% of the classification rate
Varona et.al. [27]	CNN, LSTM, and repository figuring models	98% for CNN 78% for LSTM
Surekha Arjapure et al. [28]	Mask Region-Based CNN	accuracy = 90%
J. Javier Yebes et al. [29]	RCNN Faster RCNN Inception v2	82% for RCNN 75% for Faster RCNN Inception v2
Abhishek Kumar et al. [30]	Faster RCNN, Inception-V2	-
J. Dharmeshkar et al. [31]	YOLOv3, YOLOv2, and YOLOv3-tiny	- Precision = 0.69 for YOLOv3 - Precision = 0.46 for YOLOv2 - Precision = 0.76 for YOLOv3 tiny
Ravi Agrawal et al. [32]	CNN	Accuracy = 88%
G. B. R et al. [33]	CNN	RMSE = 3.220e-03

- The detection of the pothole is more precise. As a result, videos can be used as input and then divided into frames to locate potholes.

Improving the efficiency of a prediction technique that predicts both present and future scenarios straightforwardly.

IV. CONCLUSION

The pothole detection method is an effort to give users more information about their transit routes and ensure a safe ride. It is critical to accurately detect potholes to determine the best pavement care and rehabilitation options. Manually finding and evaluating techniques, on the other hand, is both costly and time-consuming. As a result, considerable attempts have been made to develop systems that can automatically identify and distinguish potholes, allowing for early detection and remediation, enhancing survey efficiency and pavement quality.

In this paper, we studied and presented existing pothole detection approaches and suggested a possible route for building a method that can precisely and efficiently detect potholes. Each strategy has its own set of advantages and disadvantages. The vision-based technique, when combined with AI, is the most accurate and requires minimal equipment. In the future development, the pothole dataset of Indian roads needs to be developed. An accurate deep learning-based system needs to be developed which will accurately detect the pothole on Indian roads.

REFERENCES

- [1] I. Moazzam, K. Kamal, S. Mathavan, S. Usman, M. Rahman, "Metrology and Visualization of Potholes using the Microsoft Kinect Sensor," In Proceedings of IEEE Conference on Intelligent Transport System, pp.1284- 1291, 2013
- [2] India Transport Sector. [Online]. Available: <http://www.worldbank.org/en/country/india/brief/india-safe-clean-affordable-smart-transport>
- [3] B. X. Yu, and X. Yu, Vibration-based system for pavement condition evaluation, In Proceedings of the 9th International Conference on Applications of Advanced Technology in Transportation (2006), 183-189.
- [4] K. De Zoysa, C. Keppitiyagama, G. P. Seneviratne, and WWAT Shihan, A public transport system based sensor network for road surface condition monitoring, In Proceedings of Workshop on Networked Systems for Developing Regions (2007), 1-6.
- [5] J. Erikson, L. Girod, and B. Hull, The pothole patrol: using a mobile sensor network for road surface monitoring, In Proceedings of the 6th International Conference on Mobile Systems, Applications, and Services (2008), 29-39.
- [6] A. Mednis, G. Strazdins, R. Zviedris, G. Kanonirs, and L. Selavo, Real-time pothole detection using Android smartphones with accelerometers, In Proceedings of the International Conference on Distributed Computing in Sensor Systems and Workshops (2001), 1-6.
- [7] Faith Orhan, P. Erhan Eren, "Road Hazard Detection and Sharing with Multimodal Sensor Analysis on Smartphones," In Proceedings of Int. Con. on Next Generation Mobile Apps, Services and Technologies, pp. 56-61, 2013.

- [8] H. Agrawal, A. Gupta, A. Sharma, and P. Singh, "Road Pothole Detection Mechanism using Mobile Sensors," 2021 International Conference on Technological Advancements and Innovations (ICTAI), 2021, pp. 26-31.
- [9] Hadistian Muhammad Hanif et al 2020 IOP Conf. Ser.: Earth Environ. Sci. 426 012039
- [10] C. Koch, and I. Brilakis, Pothole detection in asphalt pavement images, *Advanced Engineering Informatics*, Vol. 25 (2011), 507-515.
- [11] Buza, E., S. Omanovic, and A. Huseinovic, Stereo vision techniques in the road pavement evaluation, In *Proceedings of the 2nd International Conference on Information Technology and Computer Networks*, (2013), 48-53.
- [12] Ryu S-K, Kim T, Kim Y-R. Feature-Based Pothole Detection in Two-Dimensional Images. *Transportation Research Record*. 2015;2528(1):9-17.
- [13] Lokeshwor, H., L. K. Das, and S. Goel, Robust method for automated segmentation of frames with/without distress from road surface video clips, *Journal of Transportation Engineering*, Vol. 140 (2014), 31-41.
- [14] Koch, C., G. M. Jog, and I. Brilakis, Pothole detection with image processing and spectral clustering, *Journal of Computing in Civil Engineering*, Vol. 27, No. 4, (2013), 370-378.
- [15] B. Kang, S. Choi, "Pothole Detection System Using 2D LiDAR and Camera", 2017 Ninth International Conference on Ubiquitous and Future Networks (ICUFN), 744-746, 2017.
- [16] . Y. Li, C. Papachristous, D. Weyer, "Road Pothole Detection System Based on Stereo Vision," *Naecon 2018-IEEE National Aerospace and Electronics Conference*, 292-297, 2018.
- [17] Jo Y, Ryu S-K, Kim Y-R. Pothole Detection Based on the Features of Intensity and Motion. *Transportation Research Record*. 2016;2595(1):18-28.
- [18] K. C. P. Wang, Challenges and feasibility for comprehensive automated survey of pavement conditions, In *Proceedings of 8th International Conference on Applications of Advanced Technologies in Transportation Engineering* (2004), 531-536.
- [19] Z. Hou, K. C. P. Wang, and W. Gong, Experimentation of 3D pavement imaging through stereovision, In *Proceedings of the International Conference on Transportation Engineering* (2007), 376-381.
- [20] M. Staniek, Stereo vision techniques in the road pavement evaluation, In *Proceedings of the XXVIII International Baltic Road Conference* (2013), 1-5.
- [21] Bangalore Ramaiah, N. and Kundu, S., "Stereo Vision Based Pothole Detection System for Improved Ride Quality," *SAE Int. J. Adv. & Curr. Prac. in Mobility* 3(5):2603-2610, 2021
- [22] A. Anaissi, N. L. Dang Khoa, T. Rakotoarivelo, M. M. Alamdari, · Y. Wang, "Smart pothole detection system using vehicle-mounted sensors and machine learning," *Journal of Civil Structural Health Monitoring*, 9(1), 91-102, 2019.
- [23] K. Bansal, K. Mittal, G. Ahuja, A. Singh, S. S. Gill, "DeepBus: Machine learning based real time pothole detection system for smart transportation using IoT," *Internet Technology Letters* 3 (3), vol.156, 1-6, 2020.
- [24] Biju E.D., Antony G.C., Thottappilly F.S., Davis D., Babu A. (2022) Unseen Abyss: Implementation of Pothole Detection System Using Machine Learning. In: Pandian A.P., Palanisamy R., Narayanan M., Senju T. (eds) *Proceedings of Third International Conference on Intelligent Computing, Information and Control Systems. Advances in Intelligent Systems and Computing*, vol 1415. Springer, Singapore.
- [25] Aparna, Yukti Bhatia, Rachna Rai, Varun Gupta, Naveen Aggarwal, Aparna Akula, "Convolutional neural networks based potholes detection using thermal Imaging," *Journal of King Saud University*, 2019.
- [26] Hyunwoo Song, Kihoon Baek, and Yungcheol Byun, Pothole Detection using Machine Learning, *Advanced Science and Technology Letters*, vol.150 (AST 2018), pp.151-155.
- [27] B. Varona, A. Monteserin, A. Teyseyre "A deep learning approach to automatic road surface monitoring and pothole detection," *Personal and Ubiquitous Computing*, 24(4), 519-534, 2020.
- [28] S. Arjapure and D. R. Kalbande, "Deep Learning Model for Pothole Detection and Area Computation," 2021 International Conference on Communication information and Computing Technology (ICCICT), 2021, pp. 1-6, doi: 10.1109/ICCICT50803.2021.9510073.
- [29] J. J. Yebes, D. Montero and I. Arriola, "Learning to Automatically Catch Potholes in Worldwide Road Scene Images," in *IEEE Intelligent Transportation Systems Magazine*, vol. 13, no. 3, pp. 192-205, Fall 2021, doi: 10.1109/ITS.2019.2926370.
- [30] A. Kumar, Chakrapani, D. J. Kalita and V. P. Singh, "A Modern Pothole Detection technique using Deep Learning," 2nd International Conference on Data, Engineering and Applications (IDEA), 2020, pp. 1-5.
- [31] D. J. S. D. V, A. S A, K. R and L. Parameswaran, "Deep Learning based Detection of potholes in Indian roads using YOLO," 2020 International Conference on Inventive Computation Technologies (ICICT), 2020, pp. 381-385.
- [32] Agrawal, R., Chhadva, Y., Addagarla, S., & Chaudhari, S.T. (2021). Road Surface Classification and Subsequent Pothole Detection Using Deep Learning. 2021 2nd International Conference for Emerging Technology (INCET), 1-6.
- [33] G. B. R., C. C., S. B. Rao M., S. M., K. E., and S. J., "Deep Learning Based Pothole Detection and Reporting System," 2020 7th International Conference on Smart Structures and Systems (ICSSS), 2020, pp. 1-6.