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A Pothole Boundary Detection Algorithm using Image Segmentation Technique in Urban Road

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ABSTRACT

Urban road safety is critically undermined by the presence of potholes, which necessitate accurate detection and assessment for effective maintenance. This study introduces a specialized algorithm designed to precisely detect and delineate the boundaries of potholes using advanced image segmentation techniques. Employing Otsu's method and Canny edge detection, the algorithm seeks to accurately identify and contour the edges of potholes in urban road imagery. The research extends beyond mere detection, focusing on the accurate characterization of potholes, determining their parameters and defining their regions. Implemented in Python and utilizing libraries such as OpenCV, NumPy and Matplotlib, the algorithm is developed to be modular, thoroughly documented and performance optimized. Real-world testing is a cornerstone of this project, with field tests conducted to ensure the algorithm's effectiveness across various road conditions. Additionally, the algorithm's performance is meticulously evaluated against a diverse set of image datasets sourced from the internet, aiming to validate its robustness and reliability. The study's outcomes demonstrate the algorithm's potential to significantly contribute to road safety and infrastructure maintenance, offering a promising tool for urban road management authorities.

1. Introduction

1.1 Research Background

Urban road networks are vital arteries of cities, yet their integrity is frequently compromised by potholes, leading to significant safety hazards and economic losses [1]. Traditional methods for pothole detection and assessment often involve manual surveys and visual inspections, processes that are not only time-consuming but also prone to human error [2]. In recent years, the application of image processing techniques for automated pothole detection has emerged as a promising solution, offering the potential for greater accuracy and efficiency [3]. Despite advancements, the

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challenge of accurately identifying and characterizing potholes in diverse urban environments persists, largely due to the limitations of current algorithms in distinguishing potholes from other road anomalies under varying conditions [4]. The development of sophisticated algorithms that can precisely detect, outline and measure the dimensions of potholes is crucial for timely and effective road maintenance. This research introduces an innovative algorithm that leverages state-of-the-art image segmentation techniques, including Otsu's method and Canny edge detection, to address these challenges. By employing Python and the OpenCV library, the algorithm not only aims to improve the accuracy of pothole detection but also facilitates the detailed analysis of their characteristics, thereby enhancing urban road safety and maintenance strategies [5]. The adoption of such advanced technologies underscores the shift towards more intelligent and automated systems for urban infrastructure management, marking a significant step forward in the quest to mitigate the adverse impacts of potholes on road safety and quality [6].

1.2 Literature Review

Pothole detection and the utilization of image processing techniques have garnered substantial attention in recent years [7]. This section conducts an exhaustive exploration of the existing literature, shedding light on the diverse facets of pothole detection and its integration with image processing technologies.

1.2.1 Image segmentation

Image segmentation techniques partition an image into meaningful segments [8]. The image segmentation uses different techniques for separating pothole area and non-pothole road area from the original pothole image [9]. These approaches help isolate pothole regions from the background, enabling more accurate analysis and detection [10]. The results of the segmentation method proposed by Li *et al.,* [11] demonstrate an enhancement in the efficiency of subsequent pothole shape extraction. The primary improvement involves acquiring an initial search region. In this context, the segmentation method cantered around a geometric active contour outperforms the threshold-based segmentation methods. In recent study by Kim *et al.,* [12] provide unsupervised vision-oriented technique that circumvents the need for costly machinery, extra filtering and a dedicated training stage. Lokeshwor *et al.,* [13] proposed an automated method for detecting and assessing potholes, cracks and patches in video clips of Indian highways. Their approach involved segmentation, critical distress detection and classification and analysis of distinctive visual properties. The method achieved high accuracy for potholes and cracks, but lower accuracy for patches and struggled with distinguishing similar-looking objects. Christian Koch has introduced an innovative technique for automated pothole detection that relies on images of asphalt pavement surfaces. These images can be taken from existing survey videos or, in the future, obtained from road videos captured by everyday vehicles equipped with high-speed cameras [14]. The approach begins with dividing the pavement image into sections with defects and those without defects through a process called image segmentation [15].

1.2.2 Edge detection

Edge Detection involves identifying points in an image were brightness changes sharply and discontinuously [16]. These points are grouped into lines referred to as edges. Precise pothole localization heavily relies on effective edge detection [17] as it plays a crucial role in establishing pothole shapes, thereby facilitating accurate analysis and classification [18]. Edge detection algorithms identify abrupt changes in pixel intensity [19], outlining potential pothole boundaries. Canny edge detection, Sobel operators and Robert's operators are among the widely used methods [20-22]. Ping *et al.,* [23] proposed a pothole classification model using edge detection in road image. In Wu *et al.,* [24] the method converts RGB (red, green and blue) image data, encompassing potholes and other objects, into greyscale to minimize computation. It employs an object detection algorithm to identify all objects except potholes. The identified object is eliminated, assigning a pixel value of 255 to treat it as a background. Moreover, to extract pothole characteristics, the contour of the pothole is derived via edge detection [25]. Krishnan *et al.,* [9] an overview of edge detection and other morphological operations was provided by applying them to certain images. However, this work faced challenges in verifying the accuracy of the methods employed [26].

1.2.3 Colour thresholding

Colour thresholding involves setting specific colour ranges to isolate features of interest, such as potholes, based on colour variations [27]. This technique is effective for differentiating between the road surface and potential pothole regions [28]. A model was proposed by Institute of Electrical and Electronics Engineers [29] trained on a dataset containing 568 pothole labels. The pothole detection algorithm employs colour-based checks to reduce false positives. Given the diverse shades of grey that potholes can exhibit, colour thresholding techniques have proven effective. The proposed thresholding method, as detailed in earlier work by Du *et al.,* [30], computes the absolute differences between pairs of colour channels (|R-G|, |R-B|, |G-B|). A threshold of 10 is employed here. Any computed value surpassing this threshold indicates a departure from the typical grey colour associated with potholes. This strategy effectively captures colour variations caused by potholes while minimizing false positives. Du *et al.,* [31] implemented a model for pothole and crack detection using predefined threshold values. The detection process involved various image processing techniques [32]. A significant challenge for the system lies in predetermined threshold values, as different potholes or cracks may require distinct values [33].

1.2.4 Morphological operations

Morphological operations refine the detected pothole boundaries by adjusting their shape, improving the quality of detection result [34]. The approach put forth by Wang *et al.,* [35] primarily encompasses two key aspects: pothole detection and pothole segmentation. Initially, the detection of potholes involves morphological processing of the wavelet energy field that has been constructed. And that shown using wavelet energy fields and morphological processing can accurately detect the pothole. Koch *et al.,* [36], successfully identified pothole issues by employing morphological thinning and elliptic regression techniques, achieving an accuracy rate of 86%. Pehere *et al.,* [37] employed a method that encompasses the collection of pavement images captured by an unmanned aerial vehicle [38]. This method distinguishes pavements with potholes from standard pavements by utilizing Morphological Operations on the acquired images. The success of this approach relies on the precise extraction of the Region of Interest [39]. Once the Region of Interest is accurately extracted, pothole detection is accomplished through the application of medium filters and the implementation of morphological operations for pixel filtering, all executed within the MATLAB framework [40].

1.2.5 Image enhancement

Image enhancement techniques improve image quality and visibility of specific features [41]. In pothole detection, they can highlight pothole details to distinguish them from the background [42]. And Image enhancement clarifies pothole-related features, aiding subsequent analysis steps and boosting the overall accuracy of pothole detection [43]. However, Image Enhancement is very essential and important technique used in image processing [3]. The role of image enhancement is to improve the content visibility of an image [44].

2. Methodology

2.1 Introduction

The methodology for developing a Pothole Detection Algorithm tailored to urban road environments is unveiled. Integrating the robust capabilities of Python and the OpenCV library, the methodology unfolds across some strategic phases. The preliminary study initiates the exploration, delving into literature to glean insights into cutting-edge segmentation techniques. Following this, the data acquisition and pre-processing phase involve the collection of a diverse urban road image dataset and the application of resizing, greyscale conversion and noise reduction techniques The essence of the methodology is encapsulated in the third phase, where advanced segmentation techniques such as Otsu's Thresholding and Canny edge detection are executed using the OpenCV library. This lays the groundwork for the accurate identification of potential potholes. The subsequent phase delves into the intricacies of Connected Component Analysis and contour analysis, identifying individual potholes. Contour Analysis, Segmentation Masks.

2.2 Data Acquisition

As the initial step, gather road images with potholes in various conditions the images will be separated to apply and test the algorithm on the images. The Figure 1 shows some examples of road potholes that need to be detected by the proposed method to determine the region and identify the boundary and area for each.

Fig. 1. Different scenarios for pothole conditions

2.3 Apply Pre-Processing

The step after the data Acquisition is the pre-processing of the data and the purpose of pre-processing is to prepare the images for subsequent processing steps in addition to improving image quality, enhancing relevant features and reducing noise to make pothole region detection more accurate and robust.

2.3.1 Greyscale conversion

The first step of pre-processing is greyscale conversion, the purpose of transforming colour images as illustrated in Figure 2 to greyscale to simplify processing and reduce computational cost, most pothole detection algorithms operate on greyscale images as shown in Figure 3.

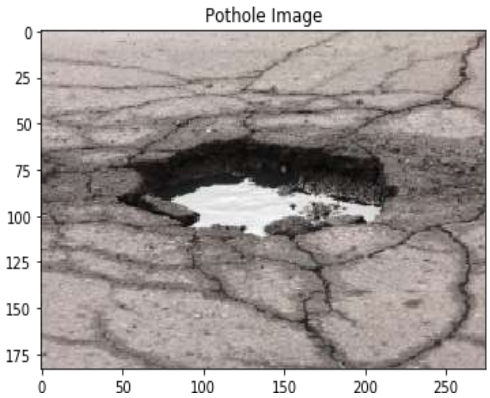

Fig. 2. Pothole original image (RGB)

Fig. 3. Pothole greyscale

2.3.2 Noise reduction

The second step of pre-processing is noise reduction and this proposed method and after the experiment, the outcome led to applying two noise reduction techniques using Gaussian blur as shown in Figure 4 and median filtering as shown in Figure 5 to suppress unwanted noise that can interfere with feature detection and segmentation, this will guarantee the efficiency of the proposed method whatever the characteristics of the image and the specific noise types because gaussian blur effective for reducing Gaussian noise (random variations in pixel intensities) and Preserves edges relatively well, essential for accurate pothole segmentation and median filtering Excels at removing salt-and-pepper noise (random black and white pixels) that made it better to preserve sharp edges. According to the pothole detection system dataset and types of image noises, after applying both techniques individually and in combination to evaluate their impact on noise reduction and edge preservation in specific images and to evaluate and refine the pre-processing pipeline to achieve the best possible results for the pothole detection system combining both techniques will be beneficial.

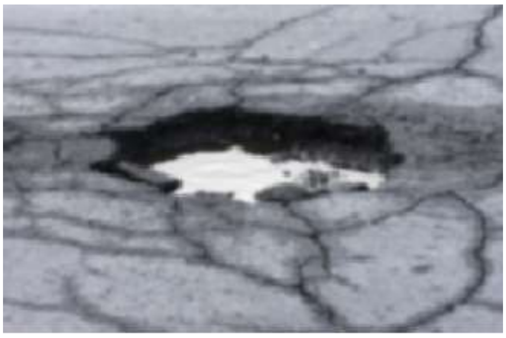

Fig. 4. Gaussian blur

Fig. 5. Median filtering

2.4 Image Segmentation and Pothole Detection

The segmentation of an image involves the technique of partitioning it into multiple sets of pixels [45]. This pivotal process serves as the foundational step for tasks like image analysis, object representation, visualization and various applications in image processing across different fields [46]. The primary aim of image segmentation is to streamline and, if needed, modify the original image sample to make it more readily analysable [47]. Thresholding is a process for image segmentation that relies on the grey-level intensity value of pixels within an image [48].

2.4.1 Thresholding

There are three image thresholding techniques used to convert greyscale images into binary images (black and white) which are simple, adaptive and Otsu's thresholding techniques. Firstly, Otsu's thresholding method entails isolating objects by transforming the greyscale image, such as a pothole image, into a binary black-and-white representation. The process of image thresholding is a useful technique for dividing an image into distinct foreground and background components [48]. Secondly, simple thresholding sets a single threshold value for the entire image, which that easy to implement as pixels with intensity values above the threshold are set to white (foreground) and those below are set to black (background) but may does not work well for complex images with multiple intensity levels or uneven lighting. In addition, the Adaptive thresholding concept applies different threshold values to different local regions of the image. It can be implemented by considering the average or weighted average of pixel intensities in a neighbourhood around each pixel to determine the threshold for that specific pixel [49]. Finally, the focus of this project is on Otsu thresholding, which stands out as one of the most widely utilized thresholding algorithms due to its simplicity, robustness and adaptability [50]. In the project, Otsu's method will be used to determine an optimal threshold value that separates the pothole regions (darker areas) from the background. Otsu's method will be used to create a binary image where pixels above the threshold are set to white (potential potholes) and those below are set to black (background).

2.4.2 Edge detection

The Canny edge detection technique was employed for pothole edge identification and segmentation in prior works [51,52]. The application involves utilizing Canny edge detection on a binary image to precisely extract the edges of potential potholes [53]. In this project, Canny edge detection will be utilized to emphasize pothole edges post-segmentation. This is because the proposed method suggests that combining the Canny edge detection technique with a Gaussian filter leads to a more effectively segmented image.

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2.5 Pothole Boundary Outlining

A contour is a continuous curve or boundary that represents the outline of an object or a region with the same intensity or colour in an image. In the proposed method contour analysis can be used to identify and analyse the boundaries of potential potholes after initial edge detection. By extracting relevant properties from the contours, such as the area or shape, one can distinguish potholes from other image features. Contours can be represented as a series of points or as a hierarchy, providing information about the relationships between different contours. Each point in the contour represents a coordinate on the boundary. Contour analysis is crucial for extracting meaningful information about objects within an image. There are two stages for contour analysis in the proposed methods Extract Contours as shown in Figure 6 and segmentation masks as shown in Figure 7. The Importance of extracting contours is to identify the actual potholes because sometimes shadows, cracks or debris are extracted by CCA as connected components. Once the true potholes are identified using contour analysis segmentation masks precisely separate the potholes from the background (pothole outlines) and this allows us to accurately identify the region of potholes.

Fig. 6. Extract contours

Fig. 7. Segmentation masks for pothole detection

3. Results

This section elucidates the outcomes derived from the deployment of the Pothole Boundary Detection Algorithm, meticulously developed using Python and the OpenCV library. The algorithm's performance was evaluated across a diverse set of road images, capturing a wide range of pothole scenarios under varying environmental conditions. The primary objective was to assess the algorithm's proficiency in accurately identifying and outlining the boundaries of potholes, thereby addressing the research gap identified in the literature review.

3.1 Algorithm Performance Overview

The algorithm was subjected to a comprehensive testing regimen, encompassing images with different levels of complexity, including variations in lighting, pothole sizes and road textures. The results demonstrated a high degree of accuracy in pothole detection, with the algorithm successfully identifying and delineating pothole boundaries across the majority of the test images.

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3.2 Example Results

Several representative examples are provided to illustrate the algorithm's effectiveness as shown in Table 1.

Table 1
Algorithm's effectiveness on pothole examples

Images description	Illustrate the algorithm's effectiveness
Clear Daylight Conditions (pothole 1)	The algorithm effectively identified all visible potholes, accurately tracing their boundaries. The precision in boundary detection facilitated a clear demarcation of the potholes from the surrounding road surface
Wet Road Surface (pothole 2)	Despite the reflective surface, the algorithm adeptly distinguished the potholes, showcasing its robustness against variations in environmental conditions.
Low-Light Conditions (Pothole 3)	The algorithm maintained a commendable level of accuracy, identifying potholes with high precision, underscoring the effectiveness of the pre-processing steps in enhancing image quality for reliable detection.

3.2.1 Example pothole 1

The illustrated case in Figure 8 exemplifies the algorithm's proficiency in navigating through the complexities of image segmentation and boundary detection. The step-by-step portrayal underscores the transformation from a raw road image to a precise delineation of a pothole, encapsulating the essence of the algorithm's intended functionality. This example vividly demonstrates the algorithm's capacity to accurately detect potholes, providing invaluable insights for road maintenance and safety enhancements.

Fig. 8. Pothole example in clear daylight conditions

3.2.2 Example pothole 2

In the provided sequence of images in Figure 9, illustrates that the algorithm is tested on a wet asphalt road. a challenging environment due to the additional reflections that can obscure the edges of potholes. Initially, the original image presents the road with a visible water-filled pothole, where the wet surface creates a reflective condition. To mitigate this, a blurring technique is applied to the second image, likely using a Gaussian blur, which helps in smoothing out the noise and diminishes the effects of reflections, thus making the true edges of the pothole more discernible. Following this, Otsu's Thresholding is employed in the third image, a binarization technique that effectively separates the pothole from the pavement by transforming the image into a stark black and white contrast, highlighting the area of the pothole despite the wet conditions. The fourth image reveals the contours detected by the Canny Edge Detection algorithm, which distinctly marks the boundaries within the wet environment. Finally, the algorithm’s ability to adapt and pinpoint the pothole's perimeter is evidenced in the last image, where the detected boundaries are overlaid on the original image with green lines. This illustrates the algorithm's precision in identifying the pothole’s edges, affirming its robustness and utility in diverse and reflective environments like wet roads, which is critical for real-world applications in road maintenance and vehicle safety.

Fig. 9. Pothole example in wet road surface

3.2.3 Example pothole 3

As illustrated in Figure 10 the results underscore the Pothole Boundary Detection Algorithm's capability to accurately identify and outline potholes in difficult environment conditions, which contributing significantly to the advancement of automated road maintenance and safety measures. The algorithm's robust performance across different environmental conditions demonstrates its applicability in real-world scenarios, marking a step forward in addressing the critical need for efficient and reliable pothole detection systems.

Fig. 10. Example pothole 3 for challenging environment

4. Conclusions

This research successfully developed a Pothole Boundary Detection Algorithm using Python and the OpenCV library, achieving significant advancements in automated pothole detection. The algorithm demonstrated high accuracy in identifying and delineating potholes across diverse road conditions, directly addressing the primary research objective. By optimizing image processing techniques, the study not only improved the efficiency and accuracy of pothole detection but also contributed to safer road conditions and more effective road maintenance strategies. The findings offer a promising foundation for future developments in road surface anomaly detection, highlighting the potential for integrating more advanced computational methods. Overall, this study marks a pivotal step towards enhancing road safety and infrastructure management through innovative computer vision applications.

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