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Pothole detection on asphalt pavements from 2D-colour pothole images using fuzzy *c*-means clustering and morphological reconstruction

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ABSTRACT

In general, potholes on asphalt pavements can be detected and represented in 2D and 3D. However, pothole detections through 3D imaging and image reconstructions have proven to be expensive in terms of acquisition equipment and the computational and processing requirements and time. For potholes at incipient formations, their detection, representation and quantification in terms of the surface-area are important for timely maintenance and repairs. By casting pavement image segmentation for pothole detection as a problem of clustering multivariate features within mixed pixels (*mixels*), this study presents a low-cost 2D vision image-based approach for the detection of potholes on asphalt road pavements in urban areas. The approach in this study is based on the *a priori* integration of multiscale texture-based image filtering for *textons* representation using wavelet transform, into the superpixel clustering of the pavement defects and non-defects using fuzzy *c*-means (FCM) algorithm. For the extraction of the defects extrema (minima and maxima) in the hybrid wavelet-FCM clustering results, fine segmentation based on morphological reconstruction is adopted to further smoothen and recognize the contour of the detected potholes. The methodology is implemented in a MATLAB prototype, tested and validated using 75 experimental image datasets. With a mean CPU run-time of 95 seconds, the average detection accuracies by comparing the study results and the manually segmented ground-truth data were determined using the Dice coefficient of similarity, Jaccard Index and sensitivity metric as 87.5%, 77.7% and 97.6% respectively. The average magnitudes of the mean and standard deviation of the percentage errors in pothole size extractions were detected as 8.5% and 4.9% respectively. The results of the study show that with well-planned road condition surveys, the proposed algorithm is suitable for the detection and extraction of incipient potholes from 2D vision images acquired using low-cost consumer-grade imaging sensors.

1. Introduction

In the recent past, a great deal of research has been dedicated to the development of innovative methods and algorithms to improve on the widely used manual-based "walk-and-record" road condition surveys. Despite the fact that automated approaches have been proposed, the manual-based pavement condition surveys are still predominantly being used [1,2], for the identification, categorization and quantification of the types and degrees of pavement defects [3,4]. In retrospect, the American Transport Research Bureau (ATRB) and the UK's Transport Research Laboratory (TRL) among other road maintenance agencies have recommended that the manual interventions be eliminated in order to reduce road survey costs, and also highlighted the drawbacks of the current automated road survey systems [2,5].

Road pavement defects can broadly be classified as surface defects and elevation-oriented defects. Potholes, patching and bleeding are surface-elevation related defects which can be categorized according to area-depth, and are mostly caused by loss of road layer aggregates as summarized in Table 1. For these types of distresses, the surface-area and depth or elevation information are an important geometric factor in determining the extent and severity of the defect.

For maintenance and repairs (M & R), potholes should be detected at the incipient stages before interfering with the road subbase or base as illustrated in Fig. 1. In such cases, the surface-areas of the detected potholes [7], become more significant than their depth d_i (Fig. 1). If early and regular road maintenance is neglected, the incipient or minor cracks on the road surface eventually cause substantial structural damage to the road, which results in part into potholes.

Notably, the detection of potholes from 2D or 3D imagery should be understood from the point of view of the pavement engineer and the contractor, when it comes to road maintenance and repairs. That is, the incipient pothole treatment as applied in partial, full-depth or injection

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Table 1
Categorization of surface elevation-based defects on flexible asphalt pavements.

Road distress category	Distress characterization and distress type image		
Area-depth or surface-elevation based road pavement distresses	 (i) Pothole	 (ii) Patching	 (iii) Excess asphalt (Bleeding)

patching is often carried out within a surface-area extent. Thus the pothole detection system is supposed to ascertain the existence of the potholes and estimate of the areal extents. This means that both the depth and diameter of the pothole defects are particularly crucial when the degree of severity of the pothole defect is of interest in M & R for purposes of ranking and prioritization.

Therefore in this study, pothole depth is not considered since the aim is to detect potholes at the initial stages before the depth exceeds the design asphalt layer depths d_1 or d_2 (Fig. 1). This implies that of significance is the detected pothole surface-area A_{d_i} for the corresponding design depth d_i. In Fig. 1, A_{Rd_i} refers to the estimated surface-area during the actual pothole treatment or repair. In scenarios where the potholes are considered to be less severe, A_{Rd_i} can be considered to be equivalent toA_{d_i}. It is also worth noting that during M & R implementations, the volume of interest is normally not the exact depth/volume of the detected pothole area, but the volume of cut as approximated by the area *abcd* in Fig. 1.

The automated pavement condition survey methods such as: 2D aerial imageries and terrestrial photogrammetric data; 2D stereo-imagery and laser point clouds, can be categorized as: (i) vibration-based accelerometers sensors [8]; (ii) 3D-stereovision techniques [9]; (iii) three-dimensional based laser scanning [10], and (iv) two-dimensional vision image based techniques [11]. Although laser-scanning systems provide highly accurate geometrical data of the pavement profile and distress detection, the cost of the sensors is still relatively high, which limits their application for routine pavement assessments [11–13]. Furthermore, the related computational approaches are expensive in terms of data processing, and the approach cannot be applied over a wide area for fast pothole detection as reported in Jo and Ryu [14] and Koch and Brilakis [11]. In contrast, the use of 2D image data for road condition surveys is widely used and has also yielded better results [4,6,84]. In general, the detection of elevation-based defects such as potholes is hindered by the costs involved in the data acquisitions and processing [4].

For this study, 2D vision images are considered appropriate for rapid and road condition survey, and for the early detection of potholes on asphalt pavements. However, 2D image processing for pavement surface assessments is a challenging task due to the inherent complexities in the image characteristics and processing for pavement defect detections [6,11,15–18].

In 2D images, pavement image segmentation is the most widely used approach for pothole detection (e.g. [7,11]). The primary segmentation methods used include thresholding, clustering and edge detection and region extraction [19,85]. These conventional methods tend to restrict each point of the data set to exclusively two clusters of data and no-data. Furthermore, hard segmentation methods cannot maintain much information which makes them suspect to noise and imaging artifacts. As a consequence, the segmentation results are often crisp, meaning that each pixel of the image belongs to exactly just one class. Most pavement surfaces images are ambiguous and have indistinguishable histograms. In such images, it is not easy for classical thresholding techniques, such as Otsu [20] and Kapur et al. [21], to find suitable criterion of similarity or closeness for thresholding, since they only work well when two consecutive gray-levels of the image are distinct. In 2D images therefore, issues such as limited spatial resolution, poor contrast, overlapping intensities, noise and intensity inhomogeneity makes hard segmentation a difficult task and often results in low accuracies in defect detection.

Statistically, image segmentation is an ambiguous problem because of the following reasons [86]. First, the statistical characteristics of local features comprising of colour, texture, edge, and contour do not usually show the same degree of homogeneity or saliency at the same spatial or quantization scale. As such segmentation results are not expected to be unique, and instead should prefer a hierarchy of segmentations at multiple scales [22]. Secondly, even after accounting for variations due to the scale, the different spectral or textural regions may still contain some intrinsic complexities, making it a difficult statistical problem to determine the correct number of segments and their dimensions. As such, a good segmentation algorithm for the detection of features should be able to group similar image pixels into regions whose statistical characteristics comprising of colour and or texture are homogeneous or stationary, and whose boundaries are simple and spatially accurate [23].

There is therefore the need to improve on the algorithms for detection of pothole geometrics including surface-area, compactness, shape, orientation and location. This study seeks to extend on the pothole detection process by using multiclass feature clustering approach, based on fuzzy *c*-means (FCM). FCM clustering is a soft

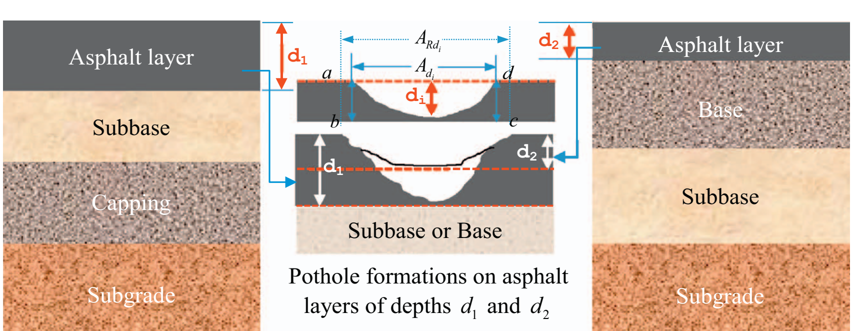

Fig. 1. One-dimensional depiction of cross-sections of flexible pavement profiles [6] and possible incipient pothole structural failures of depth d_1 and d_2 with the corresponding surface-areas A_{d_i}.