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STEREOSCOPIC MODELLING AND MONITORING OF THE ROUGHNESS IN CONCRETE PAVEMENTS

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Abstract. *The detection and measurement of surface properties, such as cracks and roughness, on concrete structures have been of significant interest in recent years. Crack formation, width and propagation as well as surface roughness are important indicators of the structural integrity and condition of a concrete pavement that can determine the need for an upgrade or maintenance operation in roads and bridges. The use of non-destructive testing techniques for development of analytical and numerical processing tools that enables the efficient measurement of surface properties is the aim of this work. In the proposed framework, a stereo camera set-up is utilised to map and register surface roughness of a concrete pavement. The benefit of using a depth image to create a surface map lies in its low-cost and ability to provide depth changes at a highly-refined level with approximately 0.05 mm accuracy. Concrete samples of different roughness are used to assess the viability of such technique in enhancing inspection ability and the effectiveness of robust structural health monitoring and assessment. The focus is placed on: the acquisition of spatial and visual data and creating a 3D point cloud mesh using XYZ and RGB data; an efficient algorithm for the registration and analysis of XYZ-RGB data; and accuracy assessment of stereo cameras in detection and measurement. The investigation herein outlined capitalises on the potential for stereo cameras in developing a pipeline for data acquisition, detection and measurement of cracks and surface roughness in concrete structures.*

Keywords: photogrammetry; single-camera; stereovision; 3D scanning; surface roughness

1 INTRODUCTION

The application of current surface characterisation techniques, such as sand-patch tests (*fib* Model Code 2010, 2013), is limited due to the inability to create detailed quantitative evaluations of the surface microtexture. Design codes currently involved in described the detailed of surface macrotexture rely on qualitative equations. Whilst this is acceptable in preliminary evaluations, it is no longer adequate for precise surface characterisations. Recent trends in surface characterisation have looked into 3D parameters as effective means of modelling and analysing surface roughness. ISO 25178-2 (2012) was established in order to standardise the increasing number of parameters for use in design. Subsequently, 3D measurement and modelling techniques have gain more popularity in characterisation methods (Fisco & Sezen, 2013; Niemczewska-Wójcik, Mathia, & Wójcik, 2014; P. M. Santos & Júlio, 2013; P. M. D. Santos & Júlio, 2010; Sezen & Fisco, 2013).

In research, photogrammetric methods have been justifiably proposed as more accurate, reliable, and cost-effective in generating important geometric and condition information of surfaces. Advances in camera technologies, post-processing computations, and effective experimental setups, both in-situ and laboratorial, creates the potential for feasible analysis and evaluation. Previous research has indicated extensive uses of photogrammetry in detailing surface roughness characteristics (Barazzetti & Scaioni, 2011; Dias-da-Costa, Valença, & Júlio, 2011; Lee & Ahn, 2004) however single camera stereo-vision approaches have not been explored. The surface analysis is consequently applied to a geometrically corrected 3D point cloud model, as opposed to defined image space coordinates typically utilised in multi-camera approaches.

2 BACKGROUND

The development of automated quantification systems for analysing road surfaces has been instrumental in characterising the influence of roughness on the response of pavements to shear. The use quantified data and evaluation adds another dimension to characterising the surface roughness of concrete pavements. The implication of which creates a robust and automated surveying system that provide a highly accurate and robust alternative to traditional methods of inspection.

3D laser scanners in texture assessment of surface roughness has been previously used as baseline test for other quantification methods (Chang, Chang, & Chen, 2005; Flintsch, de León, McGhee, & AI-Qadi, 2003; Guidi, Russo, Magrassi, & Bordegoni, 2010; P. M. D. Santos & Júlio, 2010). The use of a 3D laser scanner creates issues in terms of robustness. The scanner is not portable, therefore is limited to use in a laboratory setting, and has a high cost as well as labour intensive acquisition protocols. Despite the shortcomings, it serves as a useful baseline for the accuracy of other methods as the scanner produces a highly accurate 3D model. Hong et al. (2014) analysed three commonly used concrete aggregates (limestone, basalt and quartzite), using a 3D laser scanner to quantify the surface roughness. It was found that the bond strength of the interface increases as the roughness of the aggregate increases and has an effect on the interfacial cohesion – though little effect on the interface friction angles, that is, the way the aggregates are orientated in the concrete. Furthermore, it was observed that the compressive strength, elastic modulus and Poisson's ration of the concrete increase approximately 56.7%, 9.4% and 3.3%, respectively.

Digital image photogrammetry is a non-contact, non-destructive method of analysis. High quality images are captured from multiple views. Registered and surface characteristics are evaluated through an image processing and correlation algorithm. Features of a region of interest (ROI) are overlapped with each feature in a secondary image. (Carr & Slyder, 2016). For 3D measurements, a triangulation procedure is utilised to measure the relative displacement of objects and develop a coordinate system using stereovision methods (Helfrick, Niezrecki, Avitabile, & Schmidt, 2011). For general photogrammetry methods, circular optical targets are mounted on the surface and the centres of the targets are found through an ellipse or circle finding algorithm. In other cases, automated feature detection methods are utilised, such as corner detection procedures which are evaluated though minimum eigenvalue and feature tracking algorithms (Shi, 1994).

Efficient and accurate inspection is an important aspect of maintenance and rehabilitation of pavement surfaces. Before pavement distress, such as cracking, spalling and fatigue, can occur, it is important to characterise surface conditions during service-life, and its influence towards distress mechanisms. Further to this, but not secondary, is the usage of pavements and response of user. In order to increase the roughness of concrete pavements, surface preparation methods are employed, including: wire-brushing, sand-blasting, hydrodemolition (Silfwerbrand, 1990). Qualitative methods have been adopted for use in current design codes (EN 1992-1-1, 2004; ACI, 2014; CAN/CSA, 2004; *fib* Model Code 2010, 2013) for concrete structures. In these standards, the surface roughness and preparations are key parameters for shear stress in interfacial zone in concrete interfaces. *fib* Model Code 2010 (2013) suggests that one of the parameters influencing adhesive bonding and mechanical interlocking is the roughening of surfaces, where bonding increases with surface roughness at the interface. *fib* Model Code 2010 (2013) gives a simplified table of classification of surface roughness. Currently, Australian construction practices utilise parameters outlined in *fib* Model Code 2010, due to a lack of specificity regarding the correct design procedure in Australian standards. As these are only broad classifications, the level of detail does not always correlate with the exact surface profile and does not give a detailed specification of the surface topography.

3 OBJECTIVE AND SCOPE

The objective of this paper is to assess and evaluate the accuracy of a single-camera digital image photogrammetric method of analysis in characterizing surface roughness of concrete pavement surfaces. An experimental study where the accuracy and precision of the digital image method is compared to existing parameters of surface roughness and characterisation methods. A traditional method of quantitatively measuring surface roughness will be comparatively evaluated against a photogrammetric method for pavement roughness of different levels of qualitative textures. As a result, a low-cost, robust model for roughness characterisation is developed for use in laboratory and potentially surface analysis in-situ.

4 EXPERIMENTAL STUDY

4.1 Spatial and Visual Data Acquisition

Development of photogrammetric methods to quantify surface roughness have been somewhat limited. The application of digital image and non-contact methods using photogrammetry have been applied to soil surface roughness and topographically modelling through multi-camera and multi-view interfaces. For small scale, and especially for microscopic analysis and quantification, the accuracy of the 3D points produced from 2D images are highly dependent on the type of camera, the number and quality of images taken, the height, position and distance of where the images are taken Digital image photogrammetry has shown promise as low-cost and robust solution to surface roughness characterisation. As the method is non-destructive and efficient in application, when compared to counterparts such as laser-scanning methods, the burden on the user is reduced. Further to this, stereoscopic vision was developed to represent the texture and depth of a surface through point cloud data. The spatial and visual representation allows for the computation of depths of a region. Stereoscopy relies on the principle of using multiple images from two cameras to determine the 3D position of an environment in the same way photogrammetry allows for the measurement of objects in digital images. However, instead of simply creating a depth profile, a scene is reconstructed through a single-view from one camera where the either the camera or object moves. This Structure-from-Motion (SfM) technique uses multiple 2D images taken as a result and creates a 3D reconstruction of the scene. Ahmed, Haas, and Haas (2011) described a new system in which close-range photogrammetry was used to generate a 3D surface to monitor pavement distress. A non-metric photogrammetric method using commercial cameras and low-cost processing software captured pavement surfaces with accuracy up to 50 μm in the *x-y* plane, and 150 μm depths. El Gendy, Shalaby, Saleh, and Flintsch (2011) developed a novel system for recovering pavement surface texture from digital images and a pipeline for the application of the results and data. In the study, a photometric stereo system was developed to recover the surface heights from a region of interest on a pavement surface. The system used multiple images acquired by a camera with the surface illuminated from pre-selected positions. Surface normal were recovered from the reflection of light falling on the texture and was integrated to produce a model of the surface heights. As the experiment was conducted in a close-setting to reduce the impact of ambient lightning, the experimental setup became labour intensive. Furthermore, the restriction of lightning and control settings indicates that the method cannot be used in-situ, only in strict laboratory settings, and in a limited region of interest (100 cm^2).

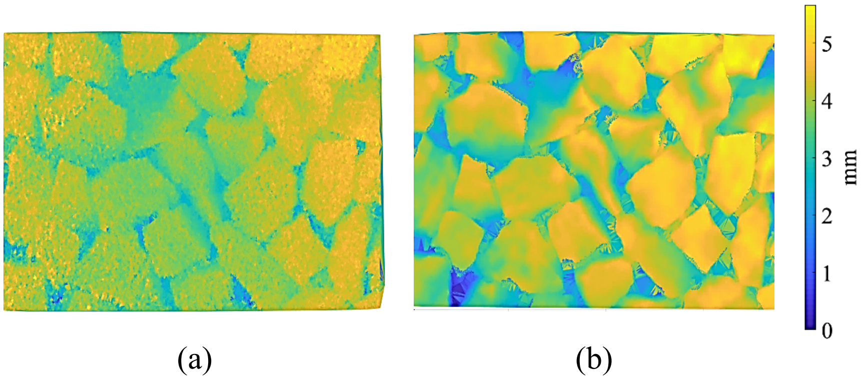
Sample data and scene reconstruction was evaluated against a reference 3D model. The spatial and visual data for the 3D model was retrieved using a AICON Scanner SmartScan 3D scanner. Spatial and visual data, and 3D digitization is performed fully automatic. A point cloud is then generated from the processed data by placing the points into a coordinate geometry – derived from the distance from the camera to the object.

The photogrammetric data was obtained with a Nikon D810 digital camera which was fitting on a tripod using 77 mm lens. During the image acquisition, the tripod and camera must be setup with a high level of consideration so as to ensure that high quality images are captured. This relates to the manner in which the camera is mounted. Implementing a stable and accurate setup of the digital camera for photogrammetry is crucial towards the accuracy of both the readings and the results. Creating a setup that is both dynamic and robust assists in developing an efficient methods of image acquisition. The camera tripod was setup in a very controlled manner – placed on a flat surface, preferably on steel plates to dampen the effects of vibration from the surrounding area.

4.2 Camera Calibration and Correlation

Camera calibration is the process by which the lens and image scene's intrinsic and extrinsic parameters are known through target point analysis in a series of images. Images are calibrated through a calibration application or software, typically within MATLAB (Bouguet, 2015). Early forms of stereovision monitoring processes were introduced by Wang and Gong (2002), in an automated condition surveying system. A four-camera system was mounted on a vehicle, fitted with high-end computers, and image acquisition and processing capabilities surveyed pavement lanes with 1-2 mm accuracy.

The image analysis procedure was conducted through MATLAB by developing a series of pipeline acquisition systems. Once the camera is calibrated, the metric information and extracted parameters can be used to reduce the lens distortion in the images. Following the calibration, a correlation algorithm is devised based on a Structure-from-motion (SfM) process outlined by (Hartley & Zisserman, 2003). Structure-from-motion refers to the 3D scene reconstruction of a region of interest based on 2D image sequences, in this case a pair of translated images. To reconstruct the 3D scene from the two images, the lens distortion and camera intrinsic parameters were first used to undistort the image. Following this, the corresponding feature between the two images were found using a feature detection algorithm. Shi (1994) proposed a method for feature selection that utilises a tracking algorithm based on a model of affine image changes, and monitoring features during tracking. The model analysing image change uses affine motion that measures the dissimilarity between computationally 'good' and 'bad' features. The method examines two different attributes that make it ideal for scene reconstructions. The first is that pure translation of the first and current image frame is not adequate for use in feature tracking as dissimilarity is often neglected or abandoned altogether. In this case, both linear warping and translations are characterised as affine image changes. MATLAB employs feature tracking capabilities that can detect specialised points and recognised 'good' features to match. Through feature matching and triangulation, the 3D points were subsequently computed to develop *xyz* coordinates for a point cloud. To add RGB data to the point cloud, a colour-based feature extraction function in MATLAB is used to retrieve the colour of each reconstructed point. The 3D point cloud is subsequently generated in MATLAB (Figure 1).



(a) (b)

Figure 1. (a) Surface plot of stereoscopic reconstruction (b) Surface plot of 3D reference scan.

4.3 Surface Roughness Parameters

The features in surface roughness analysis are diverse in the way they are characterised. Recently, the introduction of novel topometric modelling methods and increased popularity of 3D modelling have added the availability of 3D parameters to characterise surface roughness. For the case of 2D analysis, the most common parameter adopted is the *average roughness* (R_a). The use of R_a is due to its simplicity, and is defined as the average deviation of the profile in relation to its mean of the surface profile. 3D measurements and analytical methods have gained popularity in surface roughness analysis. Standardisation of 3D roughness parameters has been conducted by a European consortium (Stout, 2000) and has been classified into four categories: amplitude, spatial, hybrid and functional. The most common 3D roughness characterisation method stem from statistical measures of surface texture disparity. These descriptors can be applied to a 3D topometric models of a surface in the form of a point cloud, where the *xyz* points are analysed based on a trend in the profile.

To evaluate amplitude parameters through a stereoscopic reconstruction, systems generate a 3D model of the surface through spatial intensity images (Zhu & Brilakis, 2009). These intensity images carry information regarding how surfaces are illuminated, and spatial features are acquired through vision systems. The absorptivity and changes of light on the surface is used for analysing cracks, surface deformations, however, topographic features can be viewed and reconstructed. Methods of acquiring geometric information from the spatial features are typically acquired through structured triangulation methods, photogrammetric stereovision and laser triangulation (Pernkopf & O'Leary, 2003). Roughness parameters that use statistical analysis to evaluate surface features use coordinate geometry in the form of *xyz* coordinates. The geometrical information relates to the heights and valleys of the surface profile, and describes the three geometric quantities: planar information (*x-y* region), surface heights (*z*-values) and a combination of planar and surface heights which can be described as spatial information. This characterisation in a 3D geometrical space describes the change in slopes, trends and presence of ridges and discontinuities in the surface, which can represent sharp changes in data.

The results of the surface analysis are categorised into the quantified values based on roughness parameters: average roughness, standard deviation, root-mean-square, skewness and kurtosis. Subsequently the error in the values is calculated. The application of the single-camera stereoscopic approach enabled a smaller region of interest to be analysed. In literature, the typical topometric evaluation was conducted over a large surface area, even entire road systems. Ahmed et al. (2010) reported height accuracies between 0.115 to 0.183 mm and concluded that the approach was indeed highly accurate for the cost of the system. In this study, the use of a single-camera approach both lowers the cost, and creates a more robust solution as only one camera is required to be calibrated for real-world parameters. The focus of the analysis was to determine the stereoscopic method's accuracy when compared against a 3D scanner. Comparison against highly precise data can verify the efficacy of quantitatively evaluations through photogrammetric methods. It should be noted that there was a high variance in the stationarity of data in the photogrammetric reconstructions, compared to the smoother reconstruction of the 3D scanner.

The parameters used in this study refer to amplitude parameters. Standard deviation (σ) is one such statistical measure which outlines the variability of the surface height by quantifying the disparity against a predefined trendline establish through statistical analysis. The trendline can be defined as equal to the average value of the surface heights. The issue with simply applying the standard deviation to a data set is that the standard deviation applies a horizontal line fitted through the dispersion of surface heights along a profile. In contrast, the *root-mean-square* (RMS) heights estimates the absolute magnitude of height variation. The development of *skewness* as a characterisation method has not readily been applied to concrete pavement. With the development of 3D modelling techniques for analysis, it can be readily applied toward characterising surface profiles in combination with standard deviations, assuming the normal distribution of surface heights. Skewness is a measure which described the degree of asymmetry of a surface height distribution. Kurtosis (S_{ku}) is defined as the probability of defect occurrence and its distribution on the surface. $S_{ku} < 3$ indicates a low probability of their occurrence and their regular distribution, whereas $S_{ku} > 4$ indicates a high probability of defect occurrence and their irregular distribution.

The increased number of distortions results from the fundamental matrix relating the two views from the camera locate their positions in the real world. High levels of noise, this is, areas of increased roughness, cause noisy matches whilst computing the fundamental matrix. Further to this, the metric reconstruction of the image creates further distortions in the data set as the right shape may be retrieved. The up-to-metric scaling of the point cloud, although correct in the *x-y* plane, maybe alter the heights of the surface beyond the actual heights. Sample of the results of the parametric study for the surface and sample points are outlined in Table 5 and Table 6.

Table 1. Stereoscopic local surface roughness result: *Mean*.

Sampling Region	Stereo Reconstruction (**S**) (mm)	3D Reference Scan **(R)** (mm)	**|R – S|** (mm)	Error %
A	4.16	4.14	0.02	1
B	3.57	3.73	0.16	4
C	3.69	3.89	0.20	5
D	3.91	3.82	0.09	2
E	3.71	3.59	0.12	3
F	4.27	4.39	0.12	3

Table 2. Stereoscopic local surface roughness parameter result: *Root-Mean-Square*.

Sampling Region	Stereo Reconstruction (**S**) (mm)	3D Reference Scan **(R)** (mm)	**|R – S|** (mm)	Error %
A	4.16	4.14	0.02	1
B	3.57	3.73	0.16	4
C	3.70	3.89	0.20	5
D	3.92	3.83	0.09	2
E	3.71	3.61	0.11	3

F	4.27	4.40	0.12	3

Improvements are necessary to increase the accuracy of surface roughness classification parameters for design considerations and to increase precision. This comes down to refining the *SfM* algorithms, and conditions by which images and spatial data is acquired. The implementation of a quantitative characterisation method for surface roughness can help in achieving this goal.

5 CONCLUSION AND FUTURE WORK

The experimental results have demonstrated the potential for a single-camera stereoscopic approach to surface reconstruction in the analysis for surface roughness. Consequently, the application can range from concrete pavements, to surfaces and even aggregates. The roughness of a surface contributes to the overall quality during usage, as in the case of pavements, and more importantly towards the interfacial bonding behaviour of concrete surfaces. The low-cost reconstruction of surface characteristics enables a robust quantification system, which is more advantageous than qualitative methods currently employed in design standards. Further research potential into this area and other related aspects, include quality evaluation and monitoring of structural elements using robust and low-cost solutions. The reconstruction of 3D models gives way to the analysis of spatial information to characterise pavement distress and deformation, depth of cracks, influence of length and orientation of surface roughness. The study opens new directions of research aiming to build an analytical data system for cracks, roughness, and texture monitoring and characterisation, and improve stereovision in 3D modelling of pavements.

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