

1

2 Improved non-contact 3D field and processing 3 techniques to achieve macrotexture 4 characterisation of pavements

5 Vikki Edmondson^a, John Woodward^a, Michael Lim^a, Malal Kane^b, James Martin^a, and Islam
6 Shyha^a
7

8
9 ^a Department of Mechanical and Construction Engineering,
10 Northumbria University
11 Ellison Place
12 Newcastle Upon Tyne
13 NE1 8ST
14 United Kingdom

15
16 ^b IFSTTAR-Nantes,
17 Institut Français des Sciences et Technologiques des Transports, de l'Aménagement et des Réseaux
18 Allée des Ponts et Chaussées
19 Route de Bouaye - CS4
20 44344 Bouguenais Cedex, France
21

22 Authors Email Addresses:

23 vikki.edmondson@northumbria.ac.uk

24 john.woodward@northumbria.ac.uk

25 michael.lim@northumbria.ac.uk

26 malal.kane@ifsttar.fr

27 James.e.martin@northumbria.ac.uk

28 islam.shyha@northumbria.ac.uk

29 Full contact details of corresponding author:

30 Vikki Edmondson
31 Northumbria University
32 Ellison Place
33 Newcastle Upon Tyne
34 NE1 8ST
35 United Kingdom
36 Tel 0191 349 5930
37 Email: vikki.edmondson@northumbria.ac.uk
38

39 Abstract

40 Macrotexture is required on pavements to provide skid resistance for vehicle safety in wet
41 conditions. Increasingly, correlations between macrotexture measurements captured using non-
42 contact techniques and tyre-pavement contact friction are being investigated in order to enable
43 more robust and widescale measurement and monitoring of skid resistance. There is a notable
44 scarcity of research into the respective accuracy of the non-contact measurement techniques at
45 these scales. This paper compares three techniques: a laser profile scanner, Structure from Motion
46 photogrammetry and Terrestrial Laser Scanning (TLS). We use spectral analysis, areal surface
47 texture parameters and 2D cross-correlation analysis to evaluate the suitability of each approach
48 for characterising and monitoring pavement macrotexture. The results show that SfM can produce
49 successful measures of the areal root mean square height (Sq), which represents pavement texture
50 depth and is positively correlated with skid resistance. Significant noise in the TLS data prevented
51 agreement with the laser profiler but we show that new filtering procedures result in significantly
52 improved values for the peak density (Spd) and the arithmetic peak mean curvature (Spc), which
53 together define the shape and distribution of pavement aggregates forming macrotexture.

54 However, filtering the TLS data results in a trade-off with vertical accuracy, thus altering the
55 reliability of Sq . Finally, we show the functional areal parameters Spd and Spc are sensitive to
56 sample size. This means that pavement specimen size of 150 mm x 150 mm or smaller, when used
57 in laboratory or field observations, are inadequate to capture the true value of areal surface texture
58 parameters. The deployment of wider scale approaches such as SfM and spectrally filtered TLS are
59 required in order to successfully capture the functional areal parameters (Spc and Spd) for road
60 surfaces.

61

62 **Keywords**

63 Pavement texture; Macrottexture; Skid resistance; Structure from Motion (SfM); Terrestrial Laser
64 Scanning (TLS)

65

66

67 **1. Introduction**

68 Adequate texture on the surface of a pavement is required to provide skid resistance or friction at the
69 tyre/road interface for vehicle safety in wet conditions [1,2,3,4]. Skid resistance is also influenced by
70 temperature, presence of contaminants, speed and tyre tread thickness [5]. Friction forces generated
71 from the contact of the tyre with texture are a consequence of the viscoelastic deformation of the tyre,
72 and increase in dry conditions with adhesion [6]. Pavement texture is defined as the deviation of the
73 pavement surface from a true planar surface [7] and has been characterised at different scales according
74 to the wavelengths of the deviations [8]. Microtexture suspected to induce adhesion, represents the
75 texture components with wavelengths from less than 0.5mm and peak amplitude from 0.001 to 0.5mm.
76 Microtexture correlates to the asperities upon the surface of coarse road aggregates [9], and also to the
77 fine particles present in the mixture constituting the wearing course of the pavement. In wet conditions,
78 adhesion is reduced by the phenomenon of viscoplaning [6], where a degree of tyre contact is lost with
79 the pavement due to the presence of a thin water film (in the order of a tenth of a millimetre or less).
80 Macrottexture, suspected to induce hysteresis response in the viscoelastic tyre, represents the texture
81 components with wavelengths from 0.5 mm to 50 mm and amplitude of 0.1 mm to 20mm mm (formed
82 by the shape, size and gradation of road aggregates on a pavement surface). Macrottexture acts also to
83 disperse water, under wet conditions, through the gaps in between the road aggregates [10]. Thus,
84 macrottexture, has been shown to influence the way skid resistance reduces with increasing speed in wet
85 conditions [11]. Generally, with equal microtexture, pavement surfaces with higher macrottexture offer
86 more friction resistance as speed increases than pavements with lower macrottexture under the same
87 contact conditions [12, 13].

88

89

90 Thus, the preservation of adequate skid resistance requires the monitoring of macrotexture [1] to ensure
91 sufficient texture remains on the pavement to prevent skidding. Standard monitoring techniques involve
92 either a sand patch test [14] or a direct measurement of the frictional resistance through a rubber pad
93 [15] or test wheel making contact with a wetted pavement [16,17]. Kogbara *et al.* [18] provide a full
94 summary of devices and their operating principles. These contact devices are known to be susceptible to
95 seasonal variation [19]. This phenomenon has been attributed to a number of factors: the sensitivity of
96 rubber resilience to temperature change [20]; changes induced by temperature in the viscosity of the test
97 water of a device [21]; and differential polishing of the aggregate microtexture throughout the year [22].
98 Survey results obtained from these devices require statistical interpretation [1,23,] with individual devices
99 requiring harmonisation with the rest of a fleet [24]. Friction measurements from rubber contact base
100 devices are also known to be susceptible to changes in travel speed [25]. Direct comparison between
101 different devices adopted in particular countries is also difficult, as measurements are influenced by
102 machine operating conditions such as the load, speed, slip ratio and the composition of the rubber.

103

104 The problems associated with contact measurement techniques, make a reliable non-contact technique
105 desirable. Accurate non-contact macrotexture measurement is one step towards the estimation of
106 pavement friction values via analytical modelling [5,26,27,28]. Researchers have successfully deployed
107 contactless techniques under laboratory conditions to measure texture; typically to a size of 100 x 100
108 mm [29,30]. At present, there are also a number of in-situ proprietary spot contactless techniques
109 available for use in the field, including the Circular Texture Meter [31], the Model 9300 laser texture
110 scanner [32] and close-range stereo photogrammetry [33,34,35], which requires a minimum of three
111 images taken from different perspectives to reconstruct a 3D pavement surface. These techniques offer
112 an alternative to the simple sand patch test [14,36,37], where a measured volume of fine material is
113 spread in a circular motion into a road's surface depressions to find the mean texture depth, for in-situ
114 localised pavement texture assessment. Recent research, focused on the development of a prototype
115 test rig [38] adopting a laser range finder, that uses triangulation, to measure texture in the field or to
116 detect defect on pavements [39], but is still restricted to a localised area comparable to that of a sand
117 patch test. The minimum texture profile height measured by the rig was limited to 0.032 mm, with a

118 spatial sampling frequency of about 4 mm^{-1} , thus meeting only part of the range needed for macrotexture.
119 3D handheld scanners [40, 41], using triangulation principles, have also been deployed to capture
120 macrotexture in-situ [42]. These scanners are designed for metrology applications, and having a limited
121 field of view, lack scalability. Advances in 'off-the-shelf' laser and photogrammetry technology and point
122 cloud post-processing applications means there is now the potential to capture macrotexture over larger
123 areas, potentially more representative areas using contactless techniques. Terrestrial Laser Scanning (TLS)
124 offers rapid, full 3D high resolution reconstruction of a highway surface as a point cloud [43] and Structure
125 from Motion (SfM) photogrammetry [44,45] offers a low-cost method utilising digital images to generate
126 a 3D dense point cloud data of surfaces.

127

128 This paper introduces a method to characterise macrotexture using TLS and SfM over a typical full lane
129 width. Recent research [34] suggests that frictional resistance is sensitive to certain areal parameters
130 [46,47] (Table 1). Particularly, to the density of peaks within the macrotexture of a highway surface, Spd ,
131 and to the pointiness or arithmetic mean of the principal curvature of the same peaks Sp_c ; which together
132 characterise the shape and size of the road aggregates. Furthermore, the areal parameters root mean
133 square of surface departures, S_q , as the standard deviation of peak height from an average plane, is
134 spatially equivalent to mean profile depth [48]. Mean profile depth represents the averaged values over
135 an overall 2D profile length, of the difference within a lateral distance (typically in the order of a
136 tyre/pavement contact) between the profile and a horizontal line through the top of the highest peak.
137 This paper explores the accuracy of the scalable TLS and SFM approaches to determining these
138 measurements in comparison to measurements achieved using a 3D Smart Laser Profile Sensor [49]. The
139 3D Smart Laser Profile Sensor was selected as an accurate well-constrained controlled dataset of 2D
140 profile macrotexture measurements from which to formulate a 3D surface, as such laser profile sensors
141 are well-understood have been deployed widely previously to capture 2D profile measurements of
142 macrotexture [50, 51, 52]. This paper will first introduce the methods applied to capture point cloud data
143 in the field using the three techniques, before rigorously considering the accuracy of results obtained
144 through the application of spectral analysis, areal parameters and 2D cross-correlation.

145 **2. Methods**

146 *2.1. Remote sensing technology*

147 *2.1.1. Terrestrial Laser Scanning*

148 The TLS data were collected using the Faro Focus 3D X Series phase-based laser scanner on a tripod
149 mounted inverted as shown in Figure 1a. The static scanner was set-up at a height of 1 m above the
150 pavement surface on a levelled tripod, and the desired scanning parameters were entered on the
151 instrument's home screen. Figure 2 details the workflow for programming the scanner's settings prior to
152 completing a scan. To retain a practical completion time for the survey, a resolution of 1/5 and quality of
153 6x was adopted, providing a scan time of 22.38 minutes. The scanner stores data on a SD memory card,
154 and this was post processed using Faro Scene 7.1 software to extract, register and align the point cloud.

155 INSERT FIGURE 1 and FIGURE 2 HERE

156 *2.1.2. Structure from Motion photogrammetry*

157 Static digital images (5472 x 3648 pixels) were captured at the test location using a digital single-lens reflex
158 camera with 50 mm fixed focal length, mounted on a camera tripod and dolly (refer to Figure 1b).
159 Following the method of [34] a minimum of 60% forward overlap and 30% sideways overlap between
160 photographs was maintained. Previous research [45] has demonstrated that capturing flat surfaces using
161 SfM with predominantly parallel images, and adopting self-calibration of camera locations can cause
162 deformation of the point cloud typified by 'doming' effects. To prevent these affects, over lapping
163 photographs, were captured at three heights (500 mm, 600 mm and 750 mm) above the pavement
164 surface, across the width of the highway (Figure 3a).

166 Agisoft Photoscan version 1.3.4.5067 software 6 was used to post process the images enabling
167 reconstruction of the overlapping photographs into a 3D point cloud. The software determines the
168 position and orientation of cameras automatically using a scale invariant feature transform (SIFT) [44].
169 The SIFT matches up identified features across the image set, to establish their 3D co-ordinates and
170 generate a sparse cloud. The sparse cloud is then densified into a dense point cloud by the software using
171 Multi View Stereo techniques [53]. Figure 3 illustrates the key stages of the construction of a point cloud
172 from the camera images. Using this approach, an area equivalent to the width of a standard road lane
173 (3.65 m) was successfully reconstructed without deformation.

174 INSERT FIGURE 3 HERE

175
176
177 *2.1.3. 3D Smart Laser Profiling*

178 The 3D Smart Laser Profile Sensor, an LMI Technologies Gocator 2350, was mounted upon a trolley at a
179 height of 500 mm (Figure 1c) and powered by a 60-volt battery. One trolley wheel made contact with a
180 digital quadrature encoder fitted to a 200 mm circumference measuring wheel. The digital encoder was
181 wired to provide a pulse signal to the 3D Smart Sensor, being programmed to produce 40,000 pulses per
182 rotation of the measuring wheel. Each pulse equates to a travel distance of 0.005 mm and this information
183 is used to enable 3D surface profiles to be captured at variable speed. The 3D Smart Laser Profile Sensor's
184 settings were programmed using Gocator Emulator version 4.6.7.17 software, installed on a conventional
185 laptop. Figure 2b details the workflow for programming the 3D Smart Laser Profile Sensor's settings prior
186 to completing a scan. The data were collected at walking speed every 201 pulses or 1.005 mm over a 3 m
187 section, with the 3D Smart Laser Profile Sensor operating at a typical field of view width of 300 mm. The
188 3D Smart Laser Profile Sensor, is equipped with the capacity to view the laser points forming the profile
189 line on the highway surface in 'real-time'. This facilitates adjustment of the laser exposure level and active
190 measurement area to accommodate ambient light levels, stray light and variability of highway surface
191 reflectivity. The surface profiles extracted from the 3D Smart Laser Profile Sensor were post processed
192 using Gocator_Emulator version 4.6.7.17 and kCSvConverter software to an ASCII xyz file format suitable
193 for point cloud post processing [54].

194 *2.2. Test location*

195 To test the three techniques a field site was selected that contained three standard types of pavement
196 surface within close proximity (Figure 4), allowing for the same ambient conditions to be assumed over
197 the surfaces. The site included a close graded dense bitumen macadam (DBM), and a gap graded hot
198 rolled asphalt (HRA), as well as surface dressing (SD). Tests were undertaken on the dry pavement surfaces
199 with permanent ground control points being installed to demarcate each surface using 16 mm survey
200 nails.

201 *2.3. Deriving macrotexture parameters from non-contact survey techniques*

202 The 3D point cloud data for the DBM, HRA and SD surfaces were captured consecutively on the same day
203 using the three different techniques. The point clouds obtained from each technique were then aligned
204 utilising the installed reference ground control points in CloudCompare v 2.10 software [55], to facilitate
205 direct comparison between the surfaces. Subsequently, 150 mm x 150 mm sample areas (representing a
206 typical laboratory specimen size) were clipped for each surface from the aligned point clouds for analysis.

207 These clipped point clouds were then loaded into MountainsMap Premium version 7.4 and the software
208 used to remove any transverse or longitudinal slope by method of least squares, and to calculate the
209 standard areal parameters as listed in Table 1, to characterise the macrotecture. Areal parameters were
210 adopted, in contrast to 2D profile parameters [56], as these are recognised as providing a more complete
211 description of a surface [46], capturing height with respect to both the 'x' and 'y' direction to characterise
212 functional aspects such as texture, shape and direction. In sampling the point cloud data to make
213 successful areal measurements it is important that Nyquist values be smaller than the smallest desired
214 surface macrotecture requiring characterisation. Nyquist sampling theorem states that the shortest
215 wavelength that can be defined from a digital dataset is two digital sample intervals long. Therefore, the
216 wavelength or sample length available to characterise pavement texture areal parameters, is defined by
217 the relationship between point cloud density and sample size.

218 INSERT TABLE 1 HERE

219 *2.4. Deriving 2D wavenumber amplitude spectra from non-contact techniques and filtering*

220 Image datasets can be analysed by MATLAB software to transform them to the wavenumber domain,
221 allowing images to be characterised by spatial frequency. Accordingly, 2D Kx-Ky wavenumber spectral
222 analyses of the samples [56] were calculated in MATLAB to determine the areal wavenumber
223 characteristics of the surfaces captured using the different techniques. To prevent spectral leakage caused
224 by discontinuities at the edges of each measured sample area, the amplitude of the signal at the outer
225 edges was attenuated using a cosine taper Tukey window that extended for 10% from the extreme edges
226 of the sample line [57]. The resulting 2D wavenumber spectra enabled the wavenumber content of the
227 data to be determined, which facilitated the selection of an appropriate 2D wavenumber filter to
228 attenuate high wavenumber noise from the macrotecture signal.

229 Examining the spectra for each non-contact technique the 3D Smart Laser Profile Sensor was the lowest
230 resolution technique, containing wavenumbers not greater than 0.1 mm^{-1} . Consequently, to achieve
231 conformity of the wavelengths for areal parameter analysis across techniques a wavenumber filter of 0.1
232 mm^{-1} was applied to the SfM and TLS data. A low pass zero phase Butterworth wavenumber filter [57]
233 was then designed to remove high wavenumber noise components from the data, up to the Nyquist
234 wavenumber [58]. The filter was applied in a two-pass process, firstly for every trace in the x-direction
235 and then the y-direction, thus creating a 2D filtered data set. Normalised 2D autocorrelations and cross-

236 correlation plots of the filtered surface data were then prepared as a means of measuring image spatial
237 similarity (as the macro-texture scale pushes the limit of conventional differencing techniques adopted
238 for identifying similarity and change in point cloud analysis [56]).

239 **3. Results and discussion**

240 Nyquist values are given in Table 2. The 3D Smart Laser Profile Sensor minimum Nyquist wavelengths
241 mean that the technique is unable to measure a small part of the lower range of macrotecture
242 wavelengths between 0.5 and 1 mm. The SfM and TLS Nyquist wavelengths mean the techniques can
243 measure the full range of macrotecture wavelengths and have the potential to also measure some part
244 of microtexture below 0.5 mm, this capability should be explored as part of a further research study. The
245 Nyquist wavelengths vary between samples, possibly because the techniques are sensitive to pavement
246 surface albedo, environmental conditions, and edge effects. Given technique sensitivity, oversampling to
247 ensure a sufficiently fine Nyquist wavelength is beneficial and in this regard adopting a higher resolution
248 technique such as TLS is advantageous. The Nyquist wavelength for a TLS, will increase with distance from
249 the laser source, because of the elongation of the beam, as the angle of incidence with a surface increases.
250 Therefore, the optimal location to acquire TLS data with an 'off-the-shelf scanner', is within a narrow cone
251 of incidence directly in line with the laser source, with data captured using an inverted head tripod set-
252 up.

253 Surface height plots for each surface scanning technique are illustrated in Figure 5. For the DBM greater
254 similarity is evident between Figure 5(a) and Figure 5(b) as the 3D Smart Laser Profile Sensor and SfM
255 techniques have similar resolution. The higher resolution of the TLS is evident in the finer granularity of
256 plot Figure 5(c). All the techniques are able to capture the voids between aggregates (e.g. i) and aggregate
257 features (e.g. ii) on the DBM surface at the same locations. Equally, for the HRA surface there is greater
258 similarity between Figure 5(e) and Figure 5(f), the data captured with the 3D Smart Laser Profile Sensor
259 and SfM techniques. The higher resolution of the TLS is evident again in the finer granularity of the edges
260 of the red chipping aggregate (Figure 5g). Finally, although the SD aggregate chippings are the smallest
261 for the three surfaces, all the techniques have still collectively identified areas of void between aggregates
262 in blue Figure 5(j) to (l)(e.g. vi) and areas of elevated macrotecture in orange located to the right and left
263 edge of each plot. Again there is greater similarity between Figure 5(j) and Figure 5(k), the data capture
264 with the 3D Smart Laser Profile Sensor and SfM technique. The higher resolution of the TLS is evident in

265 the finer granularity of plot (l). The degree of similarity between the techniques has been characterised
266 using areal parameters and 2D correlation analysis discussed in Section 3.1 and 3.2 respectively.

267 INSERT FIGURE 5 AND TABLE 2 HERE

268 3.1 Unfiltered areal parameters

269 The areal parameters derived for each technique are given in Table 2. Sq is spatially equivalent to the
270 mean profile depth that is used at present to evaluate macrotexture. Table 2 shows that Sq , for the 3D
271 Smart Laser Profile Sensor and SfM are within 0.002 mm agreement for the DBM, 0.013 mm for the SD
272 and 0.09 mm for the HRA. This presents the 3D Smart Laser Profile Sensor and SfM, as an alternative
273 method to capture texture depth. The TLS obtained results for Sq are very different, with differences in
274 comparison with the 3D Smart Laser Profile Sensor value ranging from 0.139 mm to 0.394 mm; the largest
275 value being obtained for the SD surface. The value for Sp and Sv , the maximum peak and pit heights,
276 demonstrate greater agreement between the SfM and 3D Smart Laser Profile Sensor results, than the TLS
277 technique. The variance in TLS derived parameters is because of the higher resolution nature of the data.
278 Values for Spd and Spc , which have previously been shown to have positive correlations with skid
279 resistance [34], are typically different by an order of magnitude for all the techniques and surfaces
280 considered. The variability of Spd and Spc suggests the parameters are also sensitive to resolution and
281 limits the potential to adopt unfiltered data in 'universal' across technique parametric comparison studies
282 with friction. For Ssk , the parameter defining skewness (thus indicating whether texture is positive or
283 negative), all three unfiltered techniques were able to identify the positive texture of the surfaces. The
284 skewness is sensitive to the spatial sampling resolution of the technique, with closer agreement
285 demonstrated between the SfM and 3D Smart Sensor technique.

286 3.2 2D Correlation analysis

287 Areal parameters only characterise discrete functions of surface roughness. Therefore, 2D cross-
288 correlation analysis to measure x-y and z plane similarity between images was completed. Perfect
289 correlation is characterised by a strong central peak with a value of 1. The normalised 2D cross-correlation
290 plots are shown in Figure 6. For the DBM surface a central peak is evident of 0.4492 and 0.3515 for
291 similarity between the 3D Smart Laser Profile Sensor and SfM, and 3D Smart Laser Profile Sensor and TLS
292 respectively (Figure 6 (a) and Figure 6 (d)); defining positive correlation and symmetry (or lack of shift)
293 between the wavelength frequencies. To the left of the central peak there is a dominating positive feature

294 on both plots, depicted as the yellow to red zone (e.g. Figure 6 (a)(i)), representing an area of higher
295 macrottexture departure from the surface. For the SD surface, no central peak is evident with elongated
296 bands of positive and negative agreement being visible (Figure 6 cii and ciii) for similarity between both
297 the 3D Smart Laser Profile Sensor and SfM, and 3D Smart Laser Profile Sensor and TLS. The bands arise as
298 the macrottexture of the SD surface is dominated by a repeating texture feature.

299

300 Overall, the best correlation is achieved between the 3D Smart Laser Profile Sensor and SfM measurement
301 technique for the HRA surface Figure 6(b). The plot has a clear strong centralised peak of 0.729,
302 demonstrating an alignment or lack of lateral shift between the wavelength frequencies of the two
303 techniques. The rest of the plot is generally blue indicating a general lack of secondary dominating
304 features on the surface. This can be attributed to the parity of resolution between two techniques and
305 the larger wavelength features of the HRA surface. The 2D cross-correlations affirm the areal parameter
306 results with greater agreement between the unfiltered 3D Smart Laser Profile Sensor and SfM surface
307 measurements. The 2D cross-correlation plots comparing similarity between the 3D Smart Laser Profile
308 Sensor and TLS demonstrate less agreement. The normalised cross-correlation peaks are either not
309 present or where present are lower being 0.3515 for the DBM (Figure 6(d)). This confirms the influence
310 of the higher resolution shorter wavelengths within the unfiltered data, which cause the reduction in the
311 normalised peak, and reduced agreement. After the application of a 0.1 wavenumber filter the heights of
312 the normalised 2D cross- correlation peaks increase by 16.6 to 25% demonstrating stronger agreement
313 between the 3D Smart Laser Profile Sensor and the other two techniques.

314

INSERT FIGURE 6 HERE

315 *3.3 Filtered areal parameters*

316 Surface height plots for each filtered surface scanning technique are illustrated in Figure 7. For all three

317

INSERT Figure 7 Here

318 surfaces after the application of a 0.1 mm⁻¹ wavenumber filter there is greater visual similarity between
319 all three techniques. The filter has reduced the resolution of the TLS data, removing the finer granularity,
320 to reveal the macrottexture more clearly. Furthermore, post-filtering increased agreement was achieved
321 for areal parameters *Spd* and *Spc*, previously shown to have a positive correlation with skid resistance.
322 The filtered areal parameters are shown in Table 2. The filtered *Spc* (arithmetic mean peak curvature)

323 values, related to the shape of the road aggregates, measured using the 3D Smart Laser Sensor and SfM
324 are within 0.013 mm^{-1} for the DBM and 0.067 mm^{-1} for the SD. The filtered values of *Spc* for the HRA do
325 not demonstrate agreement. The filtered *Spd* (peak density) values, related to the distribution of road
326 aggregates upon a pavement surface, measured using the 3D Smart Laser Sensor and SfM are within
327 0.00087 mm^{-2} for the DBM, 0.01417 mm^{-2} for the HRA, and 0.00044 mm^{-2} respectively for the SD. The
328 filtered *Spd* (peak density) values measured using the 3D Smart Laser Sensor and TLS are within 0.00059
329 mm^{-2} for the DBM, 0.01747 mm^{-2} for the HRA, and 0.00054 mm^{-2} for the SD. The filtered *Spd* values
330 measured using the SfM and TLS are within 0.00028 mm^{-2} for the DBM, 0.0033 mm^{-2} for the HRA, and
331 0.0001 mm^{-2} for the SD. Although an increased agreement has been achieved for *Spd* and *Spc*, importantly
332 for practical pavement characterisation of surface height departures, for the 3D Smart Laser Profile Sensor
333 and SfM techniques this is at the expense of the accuracy of *Sq*, which experiences magnification at a
334 range of four to ten times. Therefore, filtering improves spatial agreement, but at the cost of vertical
335 measurement, a factor that should be considered by researchers seeking correlations between non-
336 contact texture measurements and skid resistance. Moreover, the filtered values of *Sq* obtained from the
337 TLS whilst closer to the original unfiltered 3D Smart Laser Profile Sensor, demonstrate at best ten percent
338 accuracy; being in 0.213 mm agreement for the DBM, 1.928 mm agreement for the HRA and 0.063 mm
339 agreement for the SD. The TLS technique does offer the best balance between the vertical and spatial
340 areal functions post-filtering, fundamentally because it enables oversampling of the surfaces, with
341 correspondingly the shortest Nyquist wavelength. However, the improved resolution of the technique still
342 does not lead to sufficiently accurate measurement of *Sq*, the vertical departure heights from a pavement
343 surface. Greater technique resolution does not necessarily equate to sufficiently improved accuracy for
344 some measurements.

345 *3.4 Spectral analysis*

346 The spectra in Figure 8 illustrate the areal wavenumber characteristics of the three surface materials in
347 the 'x' and 'y' plane [55]. As wavenumber is the reciprocal of wavelength, the plots serve to demonstrate
348 differences in macrottexture characteristic between the surfaces. The spectra are sensitive both to the
349 scale of the macrottexture and the technique of measurement. The TLS has the largest spectral cloud of
350 the three techniques for all surfaces, illustrating that it is consistently the highest resolution technique.
351 Considering the SfM spectral plots, it is clear that the HRA surface has the largest wavelength features

352 represented by the brightest spectral cloud centre; whilst the DBM contains the smallest wavelength
353 features represented by the largest cloud. As a high pass filter was not applied to the cloud data, the larger
354 wavelengths in the centre of the spectral plots represent the unevenness of the surfaces. The spectra
355 reveal for the SfM technique that for the HRA the wavelengths features are typically 4 mm or larger; the
356 SD 3.5 mm or larger and DBM 2.6 mm or larger. Finally, greater similarity is generally evident between
357 the unfiltered spectra for the SfM and 3D Smart Laser Profile Sensor, as the techniques have similar
358 resolution and accuracy.

359 INSERT FIGURE 8 Here

360 *3.5 Spatial variability*

361

362 The spatial variability of Sq , Ssk , Sp , Sv , Spd and Spc for seventy-two 150 mm x 150mm samples and
363 eighteen 300 mm x 300 mm samples captured using SfM were considered for a 1.8 m x 0.9 m area of HRA
364 in Figure 9 and 10.

365 INSERT FIGURE 9 and 10 Here

366 The computed parameters (Sq , Ssk , Sp , Sv , Spd and Spc) for each individual sample, were divided into a
367 percentage of the overall maximum for each considered areal parameter, with the discrete colour
368 contrasts representing 20% . Thereby each colour represents a 20th percentile in the overall maximum
369 parameter value, and thus illustrates the variability of the parameters across the 1.8 m x 0.9 m HRA surface
370 . The 150 mm x 150 mm sample size for Sp , maximum peak height, reflects the distribution of red
371 aggregate chippings across the HRA surface. Lower peaks are encountered near the top edge of the
372 sample, where the surface is predominantly bituminous binder. Some discrete squares of increased peak
373 height are shown in dark green, representing the higher texture height of isolated red chippings.
374 Principally, the peak height values Sp are within the percentile range of 1.85 mm to 3.65 mm. The 150 mm
375 x 150 mm sample size for Sv , maximum pit height, demonstrated limited variability between separate
376 sample areas, with 87.5% of the HRA surface being within 4.4 mm to 7.4 mm. This consistency most likely
377 reflects the method of laying HRA, with the precoated red aggregate chippings being scattered across the
378 surface of the previously laid asphalt binder and rolled into the surface at a constant pressure, resulting
379 in more consistent pit heights. For vertical macrotexture characterisation parameters, such as Sv , Sp and
380 Sq spatially equivalent to the mean profile depth used at present to evaluate macrotexture, there is some

381 similarity between the location of darker colour contrast for both the 150 mm x 150 mm and 300 mm x
382 300 mm sample sizes.

383

384 There is a lack of parity between the surface characterised using the 150 mm x 150 mm sample and the
385 300 mm x 300 mm sample for *Spd*; with an increase in sample size appearing to 'smooth' the density of
386 peaks removing altogether the highest percentile range $3.42 \times 10^{-3} \text{ mm}^{-2}$ to $4.06 \times 10^{-3} \text{ mm}^{-2}$ from the 300
387 mm x 300 mm plot. The 150 mm x 150 mm samples reflect the distribution of red chippings across the
388 surface, with the lower peak densities recorded near the top and edge of the HRA surface where there is
389 predominantly bituminous binder present. The *Spd* parameter also demonstrates the greatest variability
390 between different 150 mm x 150 mm samples. *Spd* has previously been shown as being important to skid
391 resistance, with positive correlation achieved with friction measurements. However, the variability of *Spd*
392 values, means picking a representative 150 mm x 150 mm sample to characterise the whole surface to
393 correlate with friction is difficult. *Spd* represents the number of peaks in a unit area and is sensitive to
394 sample size. Figure 11 considered the influence of upscaling the sample size for areal parameters (*Sq*, *Ssk*,

395

INSERT FIGURE 11 Here

396 *Sp*, *Sv*, *Spd* and *Spc*) on the HRA surfacing capture using SfM with the point cloud extended to 1.05 m x
397 1.95m. For *Spd* the optimum sample size for the HRA surface was found to be 1050 mm x 1050mm. For
398 the vertical macrotexture parameters, the optimum sample size was found to be 750 mm x 750 mm for
399 *Sv*, 1050 mm x 1200 mm for *Sp*, and 1050 mm x 1650 mm for *Sq*.

400 For *Spc* mean curvature of peaks, the optimum sample size was discovered to be 450 mm x 450 mm for
401 the HRA surface. *Spc* was found to have the smallest sample size of all the parameters considered perhaps
402 reflecting its general lack of heterogeneity. The 150 mm x 150 mm sample size demonstrating the least
403 variability across the HRA surface of any of the areal parameters considered by the study; with 80% of the
404 samples falling within the 20% range 0.58 mm^{-1} to 0.88 mm^{-1} .

405

406 Whilst *Sq*, *Sp*, and *Sv* just capture the overall height and depth of peak and pit surface departures, *Ssk*
407 gives the location (or skewness) above and below the mean plane; consequently, providing an indication
408 of the distribution of texture available to contribute to skid resistance. For *Ssk*, both the 150mm x 150
409 mm and 300mm x 300 mm sized samples confirm that the HRA has positive texture. The split of the

410 contrasting light and dark blue squares for S_{sk} , is similar for each sample size, with the predominant
411 number of darker squares below the white diagonal line bisecting the 1.8 m x 0.9 m area (refer to Fig 10).
412 However, the location of the mean plane was determined to be sensitive to sample size, with the value of
413 S_{sk} varying. A sample size of 1050 mm x 1200 mm or smaller was found in the upscaling analysis to have
414 a negative texture confirming a positive texture, but above this size S_{sk} was shown to have a positive value
415 indicating a skew to negative texture. The change in S_{sk} can be attributed to the influence of the variability
416 of peak height with changing sample area, on the location of the mean plane. Overall reviewing individual
417 areal parameters typically used to characterise friction (S_p , S_v , S_{pd} and S_{pc}) optimal sample size, suggests
418 that a suitable sample size of 1050 mm x 1200mm is appropriate to characterise HRA; this being
419 established from the maximum size of the individual parameters

420

421 Further research should be conducted to explore the efficiency of sample sizes for areal parameters for
422 different pavement textures. As contact friction devices are known to be susceptible to seasonal variation
423 and machine operating conditions such as load, speed slip ratio and the composition of rubber, using
424 reliable non-contact areal parameter data to be able to analytically model a relationship with friction is
425 desirable. Moreover, higher resolution does not always equate to greater accuracy. It was found that
426 whilst SfM photogrammetry successfully provides an alternative method to the 3D Smart Laser Profile
427 Sensor to capture vertical pavement measurement S_v , S_p and S_q for mean profile depth estimation and
428 correlation with friction, the higher resolution TLS data contained significant inaccuracies. Furthermore,
429 the values of S_{pd} and S_{pc} , which together define the shape and distribution of pavement aggregates and
430 have previously been proven to have positive correlation with friction [34], are sensitive to resolution,
431 incurring order of magnitude differences. A 2D low pass wavenumber filter achieved improved agreement
432 with the 3D smart profiler for S_{pd} and S_{pc} parameters. Optimising such filters consistently across a range
433 of non-contact techniques is needed to achieve a 'universal' correlation between these parameters and
434 to model relationships with skid resistance. Further, as the application of such a filter has the potential
435 to impact on vertical accuracy of measurement (S_q , S_p , and S_v) for some high resolution techniques,
436 findings of this study indicate the filter should be applied only to the S_{pd} and S_{pc} spatial parameters.

437

438

439 **4. Conclusions**

440 In conclusion, the study has compared the measurement of macrotexture using three different
441 techniques. The study makes a first contribution to the establishment of reliable standardised texture
442 measurements using point cloud derived data to inform analytical prediction methods for tyre-pavement
443 contact friction without the influences of seasonal variation, measuring devices and their operating
444 conditions. Results from the analysis of the data lead to the following conclusions:

- 445 • Unfiltered close field SfM photogrammetry provides values of S_p , S_v and S_q , within an acceptable
446 degree of tolerance to those obtained from the 3D Smart Laser Profile Sensor, so as SfM
447 photogrammetry is an effective, readily scalable alternative method to capture mean profile
448 depth for pavement evaluation.
- 449 • The parameters S_{pc} and S_{pd} , for which previous studies have established an important
450 correlation with pavement friction, are sensitive to technique resolution and a 2D low pass
451 wavenumber filter needs to be applied to obtain a 'universal' measurement for pavement friction
452 assessment.
- 453 • A 2D zero-phase wavelength filter of 0.1 mm^{-1} improves S_{pd} , for the TLS and SfM techniques.
- 454 • The Nyquist wavelengths of TLS and SfM techniques mean they have the potential to measure
455 microtexture wavelengths below 0.5mm.
- 456 • TLS data are significantly improved for macrostructure surveys after 2D low pass wavenumber
457 filtering.
- 458 • Where 150 mm x 150 mm industry sample sizes are used to determine parameters from point
459 clouds data derived from non-contact techniques, these are not sufficient to correctly
460 characterise functional areal parameters to describe the spatial variability of macrotexture upon
461 a pavement. This study suggests a suitable sample size of 1050 mm x 1200mm is appropriate to
462 characterise HRA.

463

464 **References**

- 465 [1] Design Manual for Roads and Bridges, HD28/15: Skid Resistance. Norwich: The Stationary Office,
466 Office of Public Sector Information. Volume 7, Section 3, Part 1, 2015. [Online] Available at:
467 <http://www.standardsforhighways.co.uk/ha/standards/dmr/vol7/section3/hd2815.pdf>
468 (Accessed 27th January 2018)
- 469 [2] D.F. Moore, The Friction of Pneumatic Tyres, Elsevier, New York (1975) ISBN 0444413235
- 470 [3] M.KlÜppel, G.Heinrich, Rubber Friction on Self Affine Road Tracks, Rubber Chemistry and Technology,
471 73 (2001) pp. 578–606. <https://doi.org/10.5254/1.3547607>

- 472 [4] B.N.J. Persson, *Sliding Friction: Physical Principles and Applications*. Springer-Verlag, Berlin (2001)
473 ISBN 978-3-662-04283-0
- 474 [5] M.Kane, V.Edmondson, Modelling the bitumen scour effect: Enhancement of a dynamic friction
475 model to predict the skid resistance of rubber upon asphalt surfaces subject to wear by traffic polishing,
476 *Wear*, 400-401 (2018) pp100-110 <https://doi.org/10.1016/j.wear.2017.12.013>
- 477 [6] M.T.Do, V.Cerezo, Road Surface Texture and Skid Resistance, *Surface Topography: Metrology and*
478 *Properties*, 3 (2015) pp1-16 <https://doi.org/10.1088/2051-672X/3/4/043001>
- 479 [7] J.W.Hall, K.L.Smith, L.Titus-Glover, J.C.Wambold, T.J.Yager, Z.Rado, Guide for Pavement Friction: Final
480 Report for National Cooperative Highway Research Program (NCHRP) Project) 01-43, Transport
481 Research Board of the National Academies, Washington, D.C, 2009. [Online] Available at:
482 <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.464.9481&rep=rep1&type=pdf> (Accessed
483 27th January 2018)
- 484 [8] PIARC, Report of the committee on surface characterisation, in: Permanent International Association
485 of Road Congress (PIARC) XVIII World Road Congress, Brussels, 1987 [Online] Available at:
486 [https://www.piarc.org/en/publications/Congress-Proceedings/Brussels-1987/technical-committee-](https://www.piarc.org/en/publications/Congress-Proceedings/Brussels-1987/technical-committee-report.htm)
487 [report.htm](https://www.piarc.org/en/publications/Congress-Proceedings/Brussels-1987/technical-committee-report.htm) (Accessed 27th January 2018)
- 488 [9] A.Dunford, Friction and the texture of aggregate particles used in the road surface course PhD thesis,
489 University of Nottingham, UK, 2013. [Online] Available at: <http://eprints.nottingham.ac.uk/13412/>
490 (Accessed 27th January 2018)[10] A. Dunford, Road Surfaces, chapter in Leach, R. The Characterisation of
491 Areal Surface Texture. Teddington: Springer pp 337-348 (2013) ISBN-13:978-3-642-36457-0
- 492 [11] G.Flintsch, E. De Leon, K.McGhee, I.Al-Qadi, Pavement Surface Macrottexture Measurement and
493 Applications, *Transport Research Record*, 1860, (2013) <https://doi.org/10.3141/1860-19> [12] R.G.Roe,
494 R.Sinhal, The polished stone value of aggregates and in service skidding resistance, TRL report 322, TRL,
495 Crowthorne, UK , 1998 [Online] Available at: <https://trl.co.uk/reports/TRL322> (Accessed 27th January
496 2018)
- 497 [13] Z.Rado, M.Kane, An initial attempt to develop an empirical relation between texture and
498 pavement friction using the HHT approach, *Wear*, 309, 1-2 (2014) pp 233-246.
499 <https://doi.org/10.1016/j.wear.2013.11.015>
- 500 [14] BS EN 13032-1:2010, Road and airfield surface characteristics – Test method. Part 1: Measurement
501 of pavement surface macrottexture depth using volumetric patch techniques. British Standard Institute.
502 London ISBN-13: 9780580685613
- 503 [15] British Standards Institute, BS EN 13036-4:2011: Road and airfield surface characteristics of slip/skid
504 resistance of a surface: The pendulum test. London: British Standards Institute (2011). ISBN-
505 13:9780580812606
- 506 [16] British Standards Institute, BS7941-1: 2006 Method of measuring the skid resistance of pavement
507 surfaces. Sideway-force coefficient routine investigation machine. London: British Standards Institute
508 (2006). ISBN-10: 0580489973
- 509 [17] British Standards Institute, BS7941-2:2000: Method of measuring the skid resistance of pavement
510 surfaces. Test method for measurement of surface skid resistance using the Grip Tester braked wheel
511 fixed slip device. London: British Standards Institute (2000).
512 ISBN-10: 0580332101
- 513 [18] R.B.Kogbara, E.A.Masad, E.Kassem, A.T.Scarpas, K.Anupam, A state-of-the-art review of parameters
514 influencing the measurement and modelling of skid resistance of asphalt pavements, *Construction and*
515 *Building Materials*, 114, (2016) pp602-617 <https://doi.org/10.1016/j.conbuildmat.2016.04.002> [19]
516 W.Bijsterveld, M.A.de Val, Towards quantification of seasonal variation in skid resistance measurement,
517 *Road Materials and Pavement Design*, 17, (2) (2016) pp 477-486
518 <http://dx.doi.org/10.1080/14680629.2015.1090909>
- 519 [20] J.R.Hosking, G.C.Woodford, TTRL Report 738, Measurement of skidding resistance Part II. Factors
520 effecting the slipperiness of a road surface. Crowthorne: Transport and Road Research Laboratory
521 (1967) [Online] Available at: <https://trl.co.uk/reports/LR738> (Accessed 27th January 2018).
- 522 [21] M.A.Kahasawneh, R.Y.Laing, Temperature effects on the frictional properties of HMA at different
523 polishing stages, *Jordan Journal of Civil Engineering*, 6 (1) (2012) p39-53 [Online] Available at:
524 <http://www.iiste.org/Journals/index.php/JJCE/article/view/17985/18362> (Accessed 27th January 2018)
- 525 [22] R.H.Smith, *Analysing Friction in the Design of Rubber Products and their Paired Surfaces*, CRC Press
526 (Taylor and Francis Group), Boca Raton, Florida, 2008 ISBN-13:9780849381379
- 527 [23] C. Plati, K. Georgouli, A. Loizos, Utilising the seasonal variations of skid resistance to plan
528 preventative maintenance, in: M.Losa, T.Pagagiannakis (Eds), *Sustainability, Eco-Efficiency and*

529 Conservation in Transportation Infrastructure Asset Management , CRC Press (Taylor and Francis Group),
530 Boca Raton, Florida, 2014, pp509-518, ISBN-13:9781138001473

531 [24] P.D.Sanders, S.McRobbie, J.Gopaldas,H.E.Viner, Report Number PPR771 Development of a
532 reference surface for the assessment of pavement skid resistance measurement devices, Transport
533 Research Laboratory, Crowthorne (2015) [Online] Available at: <https://trl.co.uk/reports/PPR771>
534 (Accessed 27th January 2018)

535 [25] A. Dunford, PPR315 Measuring skid resistance without contact, Transport Research Laboratories,
536 Crowthorne (2008) [Online] Available at: <https://trl.co.uk/reports/PPR315> (Accessed 27th January 2018)

537 [26]M.Kane, M.T.Do, V.Cerezo, Z.Rado, C.Khelfi, Contribution to pavement friction modelling an
538 introduction to the wetting effect, International Journal of Pavement Engineering (2017) p1-12

539 [27] M.Kane, V.Cerezo, A contribution to tire/road friction modelling: From a simplified dynamic friction
540 contact model to a ‘Dynamic Friction Tester’ model, Wear, (342-343) 2015 p163-171

541 [28] A.Ueckermann, D.Wang, M.Oeser, B.Steinauer, Calculation of skid resistance from texture
542 measurements, Journal of Traffic and Transportation Engineering (English Edition), 2 (1) (2015) p3-16
543 <https://doi.org/10.1016/j.jtte.2015.01.001>[29] X.Zhang, T.Liu, C.Liu, Z.Chen, Research on skid
544 resistance of asphalt pavement based on three-dimensional laser-scanning technology and pressure-
545 sensitive film, Construction and Building Materials, 69 (2014) pp49-59
546 <http://dx.doi.org/10.1016/j.conbuildmat.2014.07.015>

547 [30] V.M.C. Araujo, I.S.Bessa, V.T.F Castelo Branco, Measuring skid resistance of hot mix asphalt using
548 the aggregate image measurement system (AIMS), Construction and Building Materials, 98 (2015)
549 pp476-481 <http://dx.doi.org/10.1016/j.conbuildmat.2015.08.117>[31]B.Prowell, D.Hanson, Evaluation of
550 Circular Texture Meter for measuring surface texture of pavements, Transport Research Record: Journal
551 of the Transportation Research Board 1929, <https://doi.org/10.3141/1929-11>

552 [32] S.Li, S.Noureldin, K.Zhu,Y.Jaing, Pavement surface microtexture: Testing characterisation and
553 frictional interpretation, in B.Choubane (Ed.) Pavement Performance: Current Trends, Advance and
554 Challenges; ASTM STP 1555, American Society for Testing Materials (ASTM), West Conshohocken, PA,
555 2012 pp59-76 <http://dx.doi.org/10.1520/STP104426>

556 [33] A.Shalaby, A.El Gendy, Digital Image Analysis: Current Practice of Pavement Texture Measurement ,
557 8th International Transportation Speciality Conference, Winnipeg, Manitoba, June 9th to 12th (2010)
558 pp1313 to 1321 [Online]
559 [https://www.researchgate.net/publication/290284577_Digital_image_analysis_Current_practice_of_pa](https://www.researchgate.net/publication/290284577_Digital_image_analysis_Current_practice_of_pavement_texture_measurement)
560 [vement_texture_measurement](https://www.researchgate.net/publication/290284577_Digital_image_analysis_Current_practice_of_pavement_texture_measurement) (Accessed 27th January 2018)

561 [34] R.B. Kogbara, E.A. Masad, D.Woodward, P.Millar, Relating surface texture parameters from close
562 range photogrammetry, Construction and Building Materials, 166 (2018) pp227-240
563 <https://doi.org/10.1016/j.conbuildmat.2018.01.102>

564 [35] M.N.Alamdarlo, S.Hasami, Optimization of the photometric stereo method for measuring pavement
565 texture properties, Measurement, 127 (2018) pp406-413
566 <https://doi.org/10.1016/j.measurement.2018.05.109>

567 [36] F.G.Pratico, A.Astolfi, A new and simplified approach to assess the pavement surface micro- and
568 macrotecture, Construction and Building Materials, 148 (2017) pp 476-483.
569 <https://doi.org/10.1016/j.conbuildmat.2017.05.050>

570 [37] L.Gao, M.Lui, Z.Wang, J.Xie, S.Jia, Correction of texture depth of porous asphalt pavement based on
571 CT scanning technique,Construction and Building Materials, 200 (2019) pp 514-520.
572 <https://doi.org/10.1016/j.conbuildmat.2018.12.154>

573 [38] W.Wang, X.Yan,H.Huang,X.Chu, M.Abdel-Aty, Design and verification of a laser based device for
574 pavement macrotecture measurement, Transport Research Part C, 19 (2011) p682-694

575 [39] D.Zhang, Q.Zou, H.Lin, X.Xu, L.He, R.Gui, Q.Li, Automatic pavement defect detection using 3D laser
576 profiling technology, Automation in Construction, 96 (2018) pp 350-365
577 <https://doi.org/10.1016/j.autcon.2018.09.019>

578 [40]Creaform (no date) HandyScan 3D, The truly portable metrology grade 3D-Scanner, [Online]
579 Available at:
580 [https://www.creaform3d.com/sites/default/files/assets/brochures/files/handyscan3d_brochure_en_hq](https://www.creaform3d.com/sites/default/files/assets/brochures/files/handyscan3d_brochure_en_hq_21032017_2.pdf)
581 [_21032017_2.pdf](https://www.creaform3d.com/sites/default/files/assets/brochures/files/handyscan3d_brochure_en_hq_21032017_2.pdf) (Accessed 27th January 2018)

582 [41] Z Corporation (no date) Z Scanner ® 800 High Resolution Handheld Scanner, [Online] Available at:
583 <http://www.agile-manufacturing.com/files/products/zscanner-800.pdf> (Accessed 27th January 2018)

584 [42] L.Hu, D.Yun, Z.Lui, S.Du, Z.Zhang, Y.Bao, Effect of three-dimensional macrotecture characteristics on
585 dynamic frictional coefficient of asphalt pavement surface, Construction and Building Materials, 126
586 (2016) pp720-729 <http://dx.doi.org/10.1016/j.conbuildmat.2016.09.088>

587 [\[43\] A.Abellan, M.Jaboyedoff, T.Oppikofer, J.M.Vilaplana, Detection of millimetric deformation using a](#)
588 [terrestrial laser scanner: experiment and application to a rockfall event, *Natural Hazards and Earth*](#)
589 [System Sciences, 9 \(2009\) pp365-372](#) <https://doi.org/10.5194/nhess-9-365-2009>
590 [44] N.Micheletti, J.H.Chandler, S.N.Lane, Structure from Motion (SfM) Photogrammetry,
591 Geomorphological Techniques, Chapter 2.2 (2015) ISSN 2047-0371 [Online]
592 http://geomorphology.org.uk/geomorph_techniques (Accessed 27th January 2017)
593 [45] M.R.James, S.Robson, Straightforward reconstruction of 3D surfaces and topography with a camera:
594 Accuracy and geoscience application, *Journal of Geophysical Research*, 117 (2012) pp1-17
595 <http://dx.doi.org/10.1029/2011JF002289>
596 [46] Leach, R. Introduction to surface topography, chapter in R.Leach (eds) *Characterisation of Areal*
597 *Surface Texture*, London, Springer, (2013) pp1-13 ISBN-13:978364236457
598 [47] G.Boscaino, F.G.Praticò A classification of surface texture indices of pavement surfaces
599 [Classification et inventaire des indicateurs de la texture superficielle des revêtements des chaussées],
600 *Bulletin des Laboratoires des Ponts et Chaussées* 234 (2001), pp. 17-34+123+125+127. ISSN: 1269-1496.
601 [48] ISO 13473-1: Characterisation of pavement texture by the use of surface profiles – Part 1:
602 determination of mean profile depth. Geneva, Switzerland: International Organization for
603 Standardization (2019) [Online] Available at [https://www.iso.org/obp/ui/#iso:std:iso:13473:-1:ed-](https://www.iso.org/obp/ui/#iso:std:iso:13473:-1:ed-2:v1:en)
604 [2:v1:en](https://www.iso.org/obp/ui/#iso:std:iso:13473:-1:ed-2:v1:en) (Accessed 3rd July 2018)
605 [49] LMI Technologies (ND), Gocator 2300 series all in one smart profile sensor, Available at:
606 [https://www.stemmer-imaging.co.uk/media/uploads/vision-systems/lmi/81/81688-](https://www.stemmer-imaging.co.uk/media/uploads/vision-systems/lmi/81/81688-LMI_Gocator_2300.pdf)
607 [LMI_Gocator_2300.pdf](https://www.stemmer-imaging.co.uk/media/uploads/vision-systems/lmi/81/81688-LMI_Gocator_2300.pdf) (Accessed 18th March 2018)
608 [50] H.Yaacob, N.A.Hassan, M.R.Hainin, M.F.Rosli, Comparison of sand patch test and multi laser
609 profiles in pavement surface measurement, *Jurnal Teknologi*, 70 (4) (2014) pp 103-106
610 <http://dx.doi.org/10.11113/jt.v70.3497>
611 [51] ISO 25178 Part 2, Geometrical product specification (GPS) – Surface texture: areal part 1: terms,
612 definitions and surface texture parameters. International Organisation of Standardisation. (2012)
613 [Online] Available at: <https://www.iso.org/standard/42785.html> (Accessed 27th January 2018)
614 [52] ISO 4288. Geometrical Product Specification (GPS) -- Surface texture: Profile method -- Rules and
615 procedures for the assessment of surface texture. Geneva, Switzerland: International Organization for
616 Standardization (1996) [Online] Available at <https://www.iso.org/standard/2096.html> (Accessed 3rd July
617 2018)
618 [53] Y.Furukawa, J.Ponce, Accurate, dense, and robust multiview stereopsis, *IEEE Transactions on*
619 *Pattern Analysis and Machine Intelligence*, 32 (2010) pp 1362-1376,
620 <http://dx.doi.org/10.1109/TPAMI.2009.161>
621 [54] LMI Technologies, Gocator Firmware 4.6, The Latest Features and Tools (ND), Available at:
622 <https://lmi3d.com/products/gocator/firmware> (Accessed 27th April 2018)
623 [55] Girardeau-Montaut, D. Cloudcompare 3D point cloud and mesh processing software – open source
624 project, Available at: <http://www.danielgm.net/cc/> (Accessed 27th April 2018)
625 [56] Gubbins, D. *Time Series Analysis and Inverse Theory for Geophysicists*, Cambridge: Cambridge
626 University Press (2004) ISBN-10:0521819652
627 [57] ISO 4287, Geometrical product specification (GPS)- Surface texture: profile method – terms,
628 definitions and surface texture parameters. International Organisation of Standardisation. (1997)
629 [Online] Available at: <https://www.iso.org/standard/10132.html> (Accessed 27th January 2018)
630 [58] Bloomfield, P. *Fourier Analysis of Time Series: An introduction*. New York: Wiley-InterScience (2000)
631 ISBN-10:0471889482