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#### DIAGNOSING CLEFT LIP PATHOLOGY IN 3D ULTRASOUND: 1 A LANDMARKING-BASED APPROACH 2

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15ABSTRACT

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17Aim of this work is to automatically diagnose and formalize prenatal cleft lip with 18 representative key points and identify the type of defect (unilateral, bilateral, right, or 19left) in three-dimensional ultrasonography (3D US). Differential Geometry has been 20used as a framework for describing facial shapes and curvatures. Then, descriptors 21coming from this field are employed for identifying the typical key points of the defect 22and its dimensions. The descriptive accurateness of these descriptors have allowed us 23to automatically extract reference points, guantitative distances, labial profiles, and to 24provide information about facial asymmetry. Eighteen foetal faces, ten of healthy 25 foetuses and eight with different types of cleft lips, have been obtained through a 26Voluson system and used for testing the algorithm. Cleft lip has been diagnosed and 27correctly characterized in all cases. Transverse and cranio-caudal length of the cleft 28have been computed and upper lip profile has been automatically extract to have a 29visual guantification of the overall labial defect. The asymmetry information obtained 30is consistent with the defect. This algorithm has been designed to support 31practitioners in identifying and classifying cleft lips. The gained results have shown 32that Differential Geometry might be a proper tool for describing faces and for 33diagnosis. 34

35Keywords: Cleft lip; dysmorphisms; landmarking; syndrome diagnosis; 3D ultrasound. 36

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### 39INTRODUCTION

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41 Three-dimensional ultrasound (US) has been introduced more than twenty years 42ago into clinical practice (Riccabona et al., 1997). Its applications on diagnosis of 43anomalies and diseases were a direct consequence of its use. In particular, cleft lip 44and palate (CLP) detection, whose incidence is 1/700 in United States (Tonni and 45Lituania, 2013), was widely addressed, as they could be difficult to be diagnosed with 46bi-dimensional US, especially in earlier gestational ages (Hata et al., 1998). In the 47effort to quantify the performance of routine ultrasonographic screening on an 48unselected population, the Eurofetus study (Grandjean et al., 1999) shows that CLP 49has the lowest rates of detection (18%) and it is diagnosed usually later in pregnancy 50(only 31.6% before 24 weeks). Furthermore, CLP is identified with a lower occurrence 51by prenatal US when the anomaly is isolated than in the cases where multiple 1 1

52anomalies coexist, as frequently noticed during autopsies following termination of 53pregnancy of foetuses with diagnosed multiple diseases (Luck et al., 1992). 54Complementarily, 3D, despite some criticisms (Maarse et al., 2010), has been 55considered more accurate than bi-dimensional data in detecting unaffected lips at less 56than 24 weeks (Pretorius et al., 1995).

57 In this work we will focus on cleft lip (CL) alone. CL, "both unilateral and 58bilateral, includes clefts involving the alveolus and hard palate anterior to the incisive 59 foramen, namely the embryological primary palate" (Demircioglu et al., 2008). The 60tested rates of antenatal detection of CL range 21-30% (Rotten and Levaillant, 2004).

Cleft lip has been associated with more than one-hundred different 61 62chromosomal abnormalities and genetic syndromes (Jones, 1993), and sometimes may 63be the only sign of a chromosomal anomaly, as trisomy 18 (Carlson, 2000), trisomy 13, 64or syndromes such as Cornelia de Lange or Smith-Lemli-Opitz (Roelfsema et al., 2007). 65Thus, an accurate scan searching for other foetal anomalies and a genetic counselling 66are paramount when a cleft lip is diagnosed. Cleft lip does not go with any palatal 67abnormality in 15-25% cases (Bäumler et al., 2011, Offerdal et al., 2008). More 68generally, if we consider CLP as a whole, the incidence of structural anomalies and 69syndromes accompanying cleft lip and palate ranges between 21% and 38% 70(Campbell et al., 2005). But it is important to note that, although they often occur with 71each other, cleft lip and palate abnormalities are "developmentally distinct processes" 72(Lee et al., 2000). In particular, the embryological origins of lips and alveolus clefts 73appear to be distinct from those of secondary palate cleft (Campbell et al., 2005).

Lee et al. (2000) used three-dimensional ultrasonography to support cleft lip 74 75and palate detection. CL was identified by an examiner as "a loss of continuity of the 76 orbicularis oris muscle from a coronal or axial view of the lips" (Lee et al., 2000), so 77the diagnosis was not automatic. Campbell et al. (2005) assessed the clinical value of 78a three-dimensional US technique, the 'reverse face' view, in the prenatal 79categorization of orofacial clefts including CL. Then, Platt et al. (2006) proposed the 80'flipped face' view to diagnose lip and palate cleftings, relying on 3D US. When a static 81volume is acquired, it is rotated 90° so that the cut plane is directed in a chin-to-nose 82plane and scrolled to examine in sequential order different zones, including lips. 83Mailáth-Pokorny et al. (2010) investigated the role of foetal MRI in the antenatal 84diagnosis of facial clefts, including cleft lip, although no particular detection technique 85has been employed. Martinez-Ten et al. (2012) investigated whether systematic 86 examination of primary and secondary palate supported the detection of face cleftings 87during first trimester. Gindes et al. (2013) studied the potential of three-dimensional 88US for palate view in foetuses at high risk for CLP. An in-depth palate assessment was 89made adopting both 2D and 3D US on the axial plane. Then, the outcoming prenatal 90diagnosis was compared to after-birth findings.

91 Some authors used landmarks as reference points. Johnson et al. (2000) 92assessed the advantages of three-dimensional US in diagnosing cleft lip. The volume 93data were displayed in two formats: three orthogonal planar images and a three-94dimensional rendered image of the foetal facial surface. The planar images were 95"rotated with the interactive display into a standard anatomic orientation, so that the 96three planar images corresponded to the frontal, sagittal, and transverse facial planes" 97(Johnson et al., 2000). The rendered image provided landmarks for the planar images. 98Roelfsema et al. (2007) used 3D US to perform foetal orofacial clefts examination and 99quantified the craniofacial variability index (CVI) in distinguishing between isolated

100cleft lip/palate and cleft lip/palate in chromosomal abnormalities or syndromes. Facial 101landmarks such as tragus, nasion, gnathion, glabella, subnasion, and others were 102employed to extract sixteen craniofacial measurements for the evaluation of after-103birth abnormal/regular orofacial development. Although none of the foetuses 104evaluated in their study was affected by cleft lip, Sepulveda et al. (2010) proposed a 105novel sonographic landmark typical of the first trimester, the 'retronasal triangle', to 106be adopted for the early screening of CP. This landmark has been termed this way 107because coronal plane displays three easily identifiable echogenic lines: the two 108maxilla frontal processes and the primary palate. Manganaro et al. (2011) studied CLP 109via MRI and ultrasound, although not 3D. Facial landmarks in the zones of forehead, 110occiput, orbits, nose, lips, chin, mandible were identified and analyzed for each foetus. 111Tonni and Lituania (2012) proposed a new three-dimensional sonographic software, the 1120miView algorithm, and applied it to unilateral CL, bilateral CLP, and isolated CP. They 113showed that 3D imaging of the foetal hard and soft palates by OmniView was 114technically easier than with previously reported 3D techniques. OmniView allowed 115visualization of all anatomical landmarks of the specific targeted zone, i.e. labia, 116primary palate, alveolar ridge, posterior palate, uvula, velum, and tongue.

117 This work introduces a methodology for automatically diagnosing cleft lip and 118assessing specific information about the detected cleft, such as transverse and cranio-119caudal lengths, upper lip outline, and a quantification of facial asymmetry.

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#### 123MATERIALS AND METHODS

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During 2013, 38 3D volumes of 38 foetuses at 22-32 weeks' gestation were 126acquired. Eight of them were foetuses affected by cleft lip. Written informed consent 127was obtained from the parents for publication of clinical details, clinical images, and 128videos. Principles outlined in the Declaration of Helsinki have been followed.

Among these acquisitions, 18 were selected and processed for the purposes of 130the study, keeping all the eight faces with cleft lip. The leftover ones were excluded 131due to damages, acquisition inaccuracy, noise, and wrong or unusable foetus's 132position, such as hands on face or similar.

133 The US equipment was a Voluson system (GE Healthcare, Wauwatosa, WI, USA), 134with a RAB 4-8 (real time 4D convex transducer probe). The GE RAB 4-8 has a 135frequency range of 4 to 8 MHz and is used for OB applications (Footprint 63.6 x 37.8 136mm, FOV 70°, V 85°x70°). Table 1 shows data details and respective scan settings. 137

	Ultrasound examination											
	Volume Ultrasound: GE Voluson e - Transducer: RAB 4-8-RS/OB											
Foe	etus		1	Sca	n Setti	ng					Defect	
Nam	Wee	Μ	Fr	TI	Quali	Т	B(°	V(°	Mix	SR	Cleft lin?	
е	k			S	ty	h					ciert iip:	
Anto	32	0,	4,2/10,8 cm/51	0,	may	3	52	65	40/6		no	
	52	52	9	Hz	1	шах	0	52	05	0		no
Dart	22	0,	3,7/11,0 cm/52	0,	may	2	50	65	50/5		20	
Bart	52	9	Hz	1	max	9	50	05	0		110	
Lisa	32	1,	4,1/9,7 cm/54	0,	max	3	53	65	40/6	II	no	

		1	Hz	1		0			0		
Gio	22	1, 1	3,6/10,2 cm/58 Hz	0, 1	max	3 0	47	65	40/6 0	II	no
Gian	22	1, 0	3,6/8,1 cm/68 Hz	0, 1	high 2	3 0	46	65	40/6 0	II	no
Paul	32	1, 1	2,8/10,9 cm/49 Hz	0, 2	max	3 0	54	65	40/6 0	II	no
Pie	32	1, 1	1,7/8,1 cm/55 Hz	0, 1	max	3 0	58	65	40/6 0	II	no
Elen a	32	0, 9	4,2/10,8 cm/47 Hz	0, 1	max	3 0	56	65	40/6 0	II	no
Fede	32	0, 9	4,4/11,1 cm/51 Hz	0, 1	max	3 0	50	65	40/6 0	II	no
Simo n	32	1, 1	3,5/9,6 cm/56 Hz	0, 1	max	3 0	50	65	40/6 0	II	no
А	32	0, 9	4,2/10,8 cm/51 Hz	0, 1	max	3 0	52	65	40/6 0	II	Unilateral complete
В	32	0, 9	3,7/11,0 cm/52 Hz	0, 1	max	2 9	50	65	50/5 0	II	Unilateral complete
С	32	0, 9	4,2/10,8 cm/47 Hz	0, 1	max	3 0	56	65	40/6 0	II	Bilateral complete
D	32	0, 9	4,4/11,1 cm/51 Hz	0, 1	max	3 0	50	65	40/6 0	II	Bilateral complete
E	22	1, 0	3,6/8,1 cm/68 Hz	0, 1	high 2	3 0	46	65	40/6 0	II	Unilateral incomplete
F	32	1, 1	4,1/9,7 cm/54 Hz	0, 1	max	3 0	53	65	40/6 0	II	Unilateral incomplete
G	32	1, 1	2,8/10,9 cm/49 Hz	0, 2	max	3 0	54	65	40/6 0	II	Unilateral complete
Н	32	1, 1	3,5/9,6 cm/56 Hz	0, 1	max	3 0	50	65	40/6 0	11	Unilateral incomplete

**Table 1.** Weeks' gestation, scan settings, and eventual cleft lip features for each baby. 139

1404D VIEW software allows to see the acquired images on three orthogonal planes: axial, 141sagittal, and coronal (Fig. 1, above). The plane chosen for the facial shell modelling is 142the midsagittal (Fig. 1, below).



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Figure 1. Multiplanar image (above) and midsagittal plane (below).

148 The distance between two successive slices is 0.4 mm. For each slice composing 149the whole facial volume, the relative DICOM format file is generated and imported into 150Simpleware ScanIP software for the three-dimensional model reconstruction. Facial 151data were collected in point clouds (shells), imported in Matlab®, triangulated, and 152converted into a squared-grid-based depth map.

153 The algorithm we developed for foetal diagnosis of cleft lip was elaborated, 154 implemented, and run on these shells. It relies on the geometrical features of foetus's 155 face in order to detect the deformation. Moreover, the algorithm identifies whether the 156cleft lip is unilateral or bilateral, localizes some key points of the deformation and 157performs tailored measurements in order to assess cleft quantification. The upper lip 158outline is also evaluated, in order to provide shape and size description of the defect. 159The geometrical descriptors used in this work are defined and described in the 160Appendix. These descriptors rely on previous work of our research group (Calignano





#### **183DETECTION OF THE DEFORMITY**

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185 Cleft lip is a gap/indentation in the upper lip. The proposed algorithm 186demonstrates that this defect could be detected via point-by-point mapping 187 geometrical descriptors on facial depth map. This indentation is characterized by high 188numerical values of coefficient e and of Curvedness Index C in correspondence to the 189zone of interest, as shown in Figure 9. Moreover, the two parts of the lip that are 190located beside the indentation are characterized by two maximums of the principal 191curvature  $k_2$ , as can be seen in Figure 10.

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193 194**Figure 9.** The behaviour of the coefficient e (left) and of the Curvedness Index C (right) in a foetus with 195cleft lip. The circle highlights the area of the gap.



#### 196

197**Figure 10.** The behaviour of the principal curvature  $k_2$  in a foetus with cleft lip. The two circles highlight 198the areas of the lip beside the gap.

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The designed algorithm adopts the previous geometrical features to detect 200 201whether the cleft lip is present or not in a foetus's face. Moreover, this algorithm is 202able to automatically distinguish between unilateral and bilateral cleft lip. It is 203composed by the following steps.

204 1. The algorithm searches if there are points whose coefficient *e* and Curvedness 205 Index C are greater than a threshold value (C>3 and e>3.5). These are the 206 geometrical features of the gap in the lip. Thresholds are set via experimentation. 207

2. If the search of the step 1 gives no results, the cleft lip is not present. 208 209 Otherwise, another check is performed in order to verify that a cleft lip is really 210 present. For each point that satisfies the conditions of step 1, the algorithm 211 searches if in its neighbourhood there are points with a high value of the 212 principal curvature  $k_2$  ( $k_2$ >0.3). These are the geometrical features of the two parts of the lip beside the gap. This further condition is needed, as in some 213

- cases the points close to the *alae* of the nose could have the same geometricalfeatures searched in step 1.
- 3. If the search of the previous step gives no results, the cleft lip is not present;otherwise it is.
- 4. In order to verify if it is an unilateral or bilateral cleft lip, the algorithm checks if
  the points that satisfy the condition of step 1 and 2 are all in the same
  neighbourhood or not. If they do not belong to the same neighbourhood, the
  cleft lip is bilateral.
- The steps of the process are explained in the scheme of Figure 11.
- In Figure 12, the points found in step 1 and 2 are shown in a shell with an unilateral cleft lip.
- In Figure 13, the points found in step 1 and 2 are shown in a shell with a bilateral cleft lip.
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Figure 11. Scheme of the process for cleft lip diagnosis.



231**Figure 12.** On the left: the points found in the first step of the algorithm. On the right: the points found in 232the second step of the algorithm.



234**Figure 13.** On the left: the points found in the first step of the algorithm. On the right: the points found in 235the second step of the algorithm.

237LOCALIZATION OF KEY POINTS

In order to quantify the deformation, four key points are automatically localized: 240the two points of the lip that are beside the cleft and the ending points of the cleft, 241shown in Figure 14.



Figure 14. The four key points of the cleft lip.

As mentioned above, the principal curvature  $k_2$  has two maximums in the first 247two points. The automatic localization algorithm:

after deformity detection, identifies two regions in the neighbourhood of thecleft, one on the right side and one on the left side;

250 2. in each region, selects the points with  $D_y < 0$ ;

251 3. maximizes the principal curvature  $k_2$ .

The other two points are located in the gap of the lip. As said above, this area is 253characterized by high values of the Curvedness Index *C* and of coefficient *e*. To extract 254these points, firstly the algorithm localizes the centre of the cleft maximizing the 255coefficient *e*. Then, it analyzes the neighbourhood of this point, moving upwards from 256the centre to the high ending point and downwards till the low ending point. The 257algorithm, for each *y* value, maximizes the coefficient *e* in a neighbourhood of the cleft 258lip. The ending points are the first two maximums that are lower than a proper 259threshold value, established via experimentation.

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262MEASUREMENT OF THE DEFORMATION AND EXTRACTION OF THE UPPER LIP 263OUTLINE

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Transverse diameter of the cleft was evaluated by computing the Euclidean 266distance between the first two points extracted; its cranio-caudal length by computing 267the Euclidean distance between the last two points extracted. These two distances, 268represented in Figure 15, are the most adopted in the estimation of cleft size. 269



#### 270 <sup>271</sup> 272

Figure 15. The transverse (horizontal) and cranio-caudal length (vertical) of the cleft.

273The outline of the upper lip was also extracted, in order to provide an extra 274information about its shape. The Curvedness Index was adopted, as it is one of the 275geometrical descriptors that more accurately highlights upper lip surface behaviour. As 276shown in Figure 16, the Curvedness Index has a maximum behaviour in 277correspondence to the upper lip. To extract the outline, for each *x* value in the upper

278lip area, the Curvedness Index is maximized. This way, we obtain a sequence of 279points, namely a line, in the 3D space that describes the upper lip area. 280



Figure 16. The Curvedness Index. The two circles highlight the upper lip area.

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### 286EVALUATION OF FACE ASYMMETRY

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Facial asymmetry was also evaluated in the cases of unilateral cleft lip. To 289perform this evaluation, the mean of the absolute value of the coefficient *e* was 290computed in both left and right parts of the mouth. By comparing these two mean 291values, we obtain an useful information about the asymmetry of the face. Coefficient *e* 292is chosen and its absolute value is taken, as in correspondence of the cleft lip two 293minimums and a maximum are present (as it was previously shown in Figure 8); the 294absolute value will avoid that the minimum and maximum behaviour will annul each 295other when the mean area is computed.

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## 299RESULTS AND DISCUSSION

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The algorithm for the diagnosis of cleft lip was tested on the eighteen 302ultrasounds (eight with cleft lip and ten without). In all these cases, the algorithm 303correctly detected the presence/absence of the cleft and, in the two shells with 304bilateral cleft lip, the algorithm detected both the clefts.

305 In the eight ultrasounds with cleft lip, the four key points were localized. In 306Figure 17 the resulting four key points are shown for each shell.





Figure 17. The resulting four key points for each shell with cleft lip.

311After having localized the four key points, transverse and the cranio-caudal length are 312computed. In Table 2, the values of these distances for each shell are shown. The unit 313of measurement is the millimetre. As can be seen, the shells that present the lowest 314cranio-caudal length are the ones with an incomplete cleft.

3	1	6

Shell		
Α	7.19	6.78
В	8.31	9.59
C (left cleft)	15.08	7.00
C (right cleft)	12.04	7.06
D (left cleft)	12.65	6.09
D (right cleft)	10.01	12.34

E	6.69	1.81	
F	6.67	1.64	
G	6.19	4.34	
Н	3.17	0.62	

 Table 2. Computed distances for each shell.

318For each shell with cleft lip, upper lip outline was extracted. Results are shown in 319Figure 18.

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# 321 322 323

Figure 18. The resulting upper lip outline for each shell with cleft lip.

324We computed facial asymmetry in the six shells with unilateral cleft lip and on the ten 325shells without cleft lip; the evaluation was not performed on the two shells with 326bilateral cleft lip. The results are shown in Table 3 (shells with unilateral cleft lip) and 4 327(shells without cleft lip).

Shell			
Α	1.08	0.41	0.68
В	1.34	0.4	0.94
E	1.10	0.36	0.74
F	0.82	0.60	0.22
G	1.09	0.33	0.76
н	0.44	0.28	0.16

**Table 3.** Results of asymmetry evaluation for shells with unilateral cleft lip.

Snell			
Anto	0.28	0.33	0.05
Bart	0.30	0.48	0.18
Elena	0.16	0.27	0.11
Fede	0.33	0.30	0.03
Gian	0.22	0.33	0.11
Gio	0.16	0.24	0.08
Lisa	0.36	0.21	0.14
Paul	0.17	0.22	0.05
Pie	0.15	0.20	0.05
Simon	0.18	0.25	0.07

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**Table 4.** Results of asymmetry evaluation for shells without cleft lip.

As can be seen in Tables 3 and 4, the difference between the two sides of the 332face is usually higher in the shells with cleft lip. The mean difference value is 0.58 mm 333in shells with cleft lip instead it is 0.09 mm in shells without cleft lip, i.e. about six 334times smaller. The shell with cleft lip with the lowest difference value is H, where an 335incomplete cleft lip is present. Probably in this case the asymmetry was not high 336because the cleft lip was not accentuated, as can be verified in Table 2, where the 337shell H has the lowest cranio-caudal length. Also, the other shell with a low difference 338value, namely shell E, presents an incomplete cleft lip. Instead, in the shells without 339cleft lip the difference between the two face sides is usually low, with values ranging 340between 0.05 and 0.18 millimetres. The highest values (Bart and Lisa) are probably 341due to the quality of the ultrasound.

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#### 345CONCLUSIONS

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This work presents a new algorithm for diagnosing cleft lip on 3D ultrasound. 348The proposed algorithm was developed with Matlab® and tested on eighteen foetuses' 349faces (eight with cleft lip and ten healthy). The algorithm automatically states whether 350the defect is present or not, classifies it (unilateral, bilateral, right, left), extracts four 351key points, transverse and cranio-caudal length of the cleft, and upper lip outline, and 352provides information on the facial asymmetry. The defect has been correctly 353diagnosed and classified for all the foetuses.

Differential Geometry provided us with a set of descriptors leading this research 355activity. The result is that these descriptors are suitable to describe facial shape and 356curvedness, allowing an accurate extraction of the interested facial features.

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363The authors declare that they have no conflicts of interest to disclose.

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473

474

475APPENDIX

476

477The First and Second Fundamental Forms are used to measure distance on surfaces 478and are defined by

479

$$480 \quad Edu^2 + 2Fdudv + Gdv^2 \quad , \tag{1}$$

(2)

481

482  $ed u^2 + 2 fdudv + gd v^2$ 

483

484respectively, where *E*, *F*, *G*, *e*, *f* and *g* are their Coefficients. Curvatures are used to 485measure how a regular surface *x* bends in  $R^3$ . If *D* is the differential and *N* is the 486normal plane of a surface, then the determinant of *DN* is the product 487  $(-k_1)(-k_2)=k_1k_2$  of the Principal Curvatures, and the trace of *DN* is the negative

488 
$$-[k_1+k_2]$$
 of the sum of Principal Curvatures. In point *P*, the determinant of  $DN_P$  is  
489the *Gaussian Curvature K* of *x* at *P*. The negative of half of the trace of *DN* is called the  
490*Mean Curvature H* of *x* at *P*. In terms of the principal curvatures can be written

491  
492 
$$K = k_1 k_2$$
, (3)  
493  
494  $H = \frac{k_1 + k_2}{2}$ .  
495 (4)  
496

497Some definitions of these descriptors are given. These are the forms implemented in 498the algorithm: 499

499		
500	$E=1+h_x^2$ ,	(5)
501		
502	$F = h_x h_y$ ,	(6)
503	$C = 1 + l^2$	
504	$G=1+h_y$ ,	(7)
505	h	
506	$e = \frac{h_{xx}}{\sqrt{1 + h_x^2 + h_y^2}}  ,$	
507 508	(8)	
509	$f = \frac{-h_{xy}}{\sqrt{1+h_x^2+h_y^2}}  ,$	
510 511	(9)	
512	$g = \frac{-h_{yy}}{\sqrt{1+h_x^2+h_y^2}} ,$	
513 514	(10)	
515	$K = \frac{h_{xx}h_{yy} - h_{xy}^{2}}{\left(1 + h_{x}^{2} + h_{y}^{2}\right)^{2}} ,$	
516 517	(11)	
518	$H = \frac{\left(1 + h_x^2\right)h_{yy} - 2h_xh_yh_{xy} + \left(1 + h_y^2\right)h_{xx}}{\left(1 + h_x^2 + h_y^2\right)^{3/2}} ,$	
519 520	(12)	
521	$k_1 = H + \sqrt{H^2 - K}  , \qquad$	
522 523	(13)	
524	$k_2 = H - \sqrt{H^2 - K}  , \qquad$	
525	(14)	

527where *h* is a differentiable function z=h(x,y). It is, therefore, convenient to have at 528hand formulas for the relevant concepts in this case. To obtain such formulas let us 529parametrize the surface by 530

531 
$$x(u,v) = (u,v,h(u,v))$$
,  $(u,v) \in U$ ,  
532 (15)  
533  
534 where  $u = x, v = y$ .  
535  
536 The most used descriptors are surely the  
537 introduced by Keenderink et  $z_1 z_1^2$ .

536The most used descriptors are surely the Shape and Curvedness Indexes *S* and *C*, 537introduced by Koenderink *et al.*<sup>1</sup>: 538

$$S = \frac{-2}{\pi} \arctan \frac{k_1 + k_2}{k_1 - k_2} , \qquad S \in [-1, 1] , \qquad k_1 \ge k_2 ,$$

$$S = \frac{-2}{\pi} \arctan \frac{k_1 + k_2}{k_1 - k_2} , \qquad S \in [-1, 1] , \qquad k_1 \ge k_2 ,$$

$$S = \sqrt{\frac{k_1^2 + k_2^2}{2}} .$$

$$S = \sqrt{\frac{k_1^2 + k_2^2}{2}} .$$

$$S = \sqrt{\frac{k_1^2 + k_2^2}{2}} .$$

### 

545For the role they play in the work, a little digression about their significance is needed. 546Their meaning is shown in Figures 19-21 and in Table 5.



**Figure 19.** Illustration of Shape Index scale divided into seven categories. Different 549subintervals of its range [-1,1] correspond to seven geometric surfaces. 

Class	S	Туре	H	K
cup/pit	[-1,-0.625)	elliptical convex	+	+
rut/valley	[-0.625,-0.375)	cylindrical convex	+	0
saddle rut/saddle valley	[-0.375,-0.125)	hyperbolic convex	+	-
saddle	[-0.125,0.125)	hyperbolic symmetric	0	-
saddle ridge	[0.125,0.375)	hyperbolic concave	-	-
ridge	[0.375,0.625)	cylindrical concave	-	0
dome/peak	[0.625,1)	elliptical concave	-	+
	Table 5. Topographic	c classes.		

<sup>431</sup> Koenderink, J.J. and van Doorn, A.J., 1992. Surface shape and curvature scales. 44Image and Vision Computing 10(8), 557-564.



**Figure 21.** Indexes (*S*,*C*) are viewed as polar coordinates in the  $[k_1, k_2]$  -plane, with planar 558points mapped to the origin. The effects on surface structure from variations in the curvedness 559(radial coordinate) and Shape Index (angular coordinate) parameters of curvature, and the 560relation of these components to the principal curvatures ( $k_1$  and  $k_2$ ). The degree of 561curvature increases radially from the centre.