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Influence of roughness on conoscopic holography digitizing of DIN34CrMo4 Surfaces

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Abstract

Conoscopic Holography is a non-contact digitizing technique used in inspection and reverse engineering tasks. A laser beam is projected onto a surface, and its reflection generates a holographic pattern inside the sensor. This pattern is later analysed and the distance between sensor and surface is calculated. Like other optical techniques, conoscopic holography shall be affected by surface properties and ambient conditions. This works deals with the influence of surface roughness and manufacturing process on the quality of digitizing. 34CrMo4 steel test specimens have been manufactured to obtain four different *Ra* levels. Two different manufacturing process, electrical discharge machining (EDM) and ball-end milling (BEM) have been also considered. Quality of the digitized point clouds under different sensor configurations has been analysed, in order to provide a recommendation for optimal capture conditions.

Keywords: Conoscopic holography; surface digitizing

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1. Introduction

Conoscopic Holography (CH) is a non-contact digitizing technique. When the reflection of a laser projected onto a surface passes through a conoscope, an interference pattern is generated and registered in a CCD. The computational analysis of this image provides a value for the distance between the sensor and the surface. Sirat et

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al. (2005) reported the advantages of CH when compared with other non-contact techniques, like laser triangulation. According to their work, CH shows better accuracy and repeatability up to 10 times for a given depth of field. CH has also shown better behaviour for a wide variety of materials and has been proved capable for measuring points upon 85° sloped surfaces.

Due to their collinear design, CH sensors can incorporate mirrors for laser light redirection to digitize hard-to-access geometries such as holes or narrow cavities. CH is being used in different industrial fields, including quality assessment, reverse engineering or in-process inspection. In these applications, accuracy assessment becomes a key factor (Álvarez et al. 2009).

Nevertheless, like other optical techniques, CH digitizing quality may be affected by surface optical properties. Lathrop et al. (2010) have applied CH technology for surface digitizing of biological tissues. In this work, sensor main configuration parameters, power (*P*) and frequency (*F*), were adjusted to provide good quality measurements. Additionally, the Signal-to-Noise Ratio (SNR) parameter, which is automatically provided by the sensor itself for every single measurement, has been used as a quality criterion. Therefore, following recommendations of the manufacturer, a minimum 50% SNR is demanded for high quality measurements. These authors have also considered repeatability as a performance indicator. They have found that the nature of surface material (colour, texture) has an influence on the digitizing quality. Consequently a specific adjustment of tuning parameters must take into account surface characteristics.

The use of SNR as a quality indicator is well established in different works (Zhu et al., 2007, Lonardo and Bruzzone 2000, and Lombardo et al.2001). However, this is an indicator of signal quality, and it is not clear if the best SNR value (the maximum one) for a particular digitizing test provides the best results according to geometrical or dimensional criterions.

Integration of a CH sensor on a CMM and the later calibration procedure have been discussed in previous works (Fernández et al. 2010) as part of a study for a better understanding of the CH technology and capabilities. Additional works (actually under review) have focused on quality differences when digitizing a wide variety of materials, including metals, plastics and reflectance standards.

The present work aims at analysing the influence of surface roughness on the quality of CH digitized surfaces. Efforts had been paid to establish an optimal configuration for sensor configuration parameters when digitizing 34CrMo4 steel machined surfaces. It must be remarked that this work does not intend to provide complex rules for the relationship between roughness and measurement results. Nevertheless it seeks for a better comprehension of the influence of roughness among quality results under different quality indicators.

2. Methodology

2.1. Test equipment

An Optimet Conoprobe Mark III sensor has been used in present work. This sensor is equipped with 50 mm focal length lens. Working range is 8 mm width and a 655 nm laser diode is used as the light source. This point-type sensor provides a single value each time for the distance between the transmitter and the surface. A relative displacement between the sensor and the surface is required in order to obtain a complete representation of its geometry. A virtual 3D representation is thereafter obtained as an array of digitized points or point cloud. As it was explained in Fernández et al. (2010), this sensor has been integrated into a Coordinate Measurement Machine (CMM) DEA Swift (Fig. 1).

2.2. Characteristics of test surfaces

In present work, 34CrMo4 steel parts have been machined to obtain planar test surfaces. Surface roughness has been characterized using the arithmetic average roughness value (*Ra*). Four *Ra* levels (0.4 µm, 0.8 µm, 1.6 µm y 3.2 µm) were selected for testing purposes. Surfaces have been machined using two different processes: electrical-discharge machining (EDM) and ball-end milling (BEM). As a result, eight different specimens have been used for testing (Table 1).

Roughness level is employed as an adjustment parameter for the ONA NX EDM machine used in this work. According to the machine characteristics, the roughness level must be expressed in the NC program in terms of the VDI 3.402 standard. This means that the EDM machine automatically selects the proper working conditions according to a given roughness requirement. The values for VDI roughness level can be calculated according to the expression $VDI = 20 \cdot \log(10 \cdot Ra)$ (Sánchez-Galíndez et al. 2006). Therefore, the corresponding values of roughness under the VDI standard become 12, 18, 24 and 30 for the Ra values of 0.4, 0.8, 1.6 and 3.2 µm, respectively.

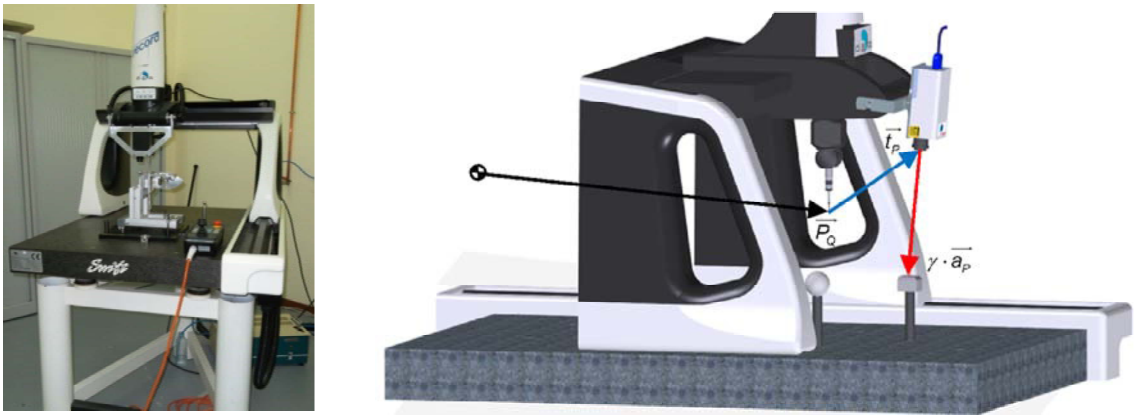
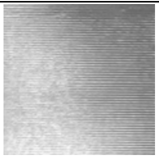
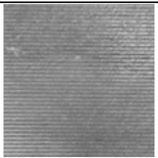
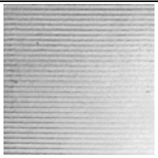
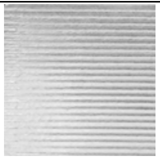
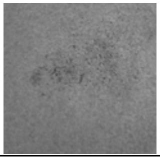
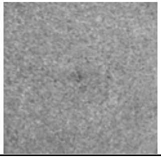


Fig. 1. Integration of the CH sensor on a DEA Swift CMM

A 30 mm diameter ($R = 15\,mm$) ball-end mill has been used for the milled surfaces. In this process, roughness has been controlled using the relation among the *Ra* values and the total height of roughness profile (R_t) (Sandvik 1994) Later, the Rt has been used for calculating the proper spacing (a_e) value following the expression given by Sánchez-Galíndez et al. (2006):

$$a_e = \sqrt{8 \cdot R \cdot Rt} \tag{1}$$

Table 1. Test surfaces

Ra (Theoretical)	*Ra*=0.4 µm	*Ra*=0.8 µm	*Ra*=1.6µm	*Ra*=3.2 µm
BEM				
EDM				

According to this, the a_e value must be 0.51 mm to obtain a 0.4 µm *Ra* surface, while the other *Ra* levels shall demand 0.69 mm, 0.98 mm and 1.22 mm a_e values respectively. Depth of cutting has been fixed to a 0.5 mm value, while feed rate has been fixed to a 200 mm/min value. Orientation of the test specimens has been also taken into account for digitizing purposes, so that the direction of feed matches the positive direction of the CMM X.

It must be remarked that slight differences were found between actual *Ra* values and the theoretical ones. As a consequence, manufacturing parameters have been slightly modified in order to reduce those differences to a ±10% range of the nominal values. Nevertheless, the nominal *Ra* has been used in this work in the description and discussion of results, instead of the measured *Ra*. As this work is focused on describing the influence of roughness upon sensor optimal configuration it has been considered that slight errors in *Ra* do not significantly affect data analysis and discussion.

2.3. Surface positioning

A fixture has been designed for a proper location and orientation of the specimens (Fig. 2). The specimen is mounted on a micrometre screw actuated mechanism, and the fixture includes a levelling system. Using these two features, the planar surface of the specimens can be oriented so that the projection of the laser beam impacts orthogonally at the optimal working location (in the middle of the sensors working range). This two-stage setup (levelling + positioning) has to be executed before each single test.

Fig. 2. Views of the CMM, the sensor, the fixture and the test surface during a scanning operation

2.4. Digitizing procedure

The objective of the digitizing procedure is to provide analogous pointclouds for different combination of digitizing parameters *P* and *F*. A full factorial design of experiments has been selected in order to achieve a global perspective of quality variations among the range limits of both parameters.

P is a non-dimensional parameter related to the intensity of the laser beam and can be modified ranging from 0 to 64. In this work, twelve levels have been used for the *P* parameter, ranging from 5 to 60 in steps of 5 units. Additionally, six levels have been considered for the digitizing frequency *F* ranging from 500 Hz to 3000 Hz, with a 500 Hz step. This design of experiments leads to 72 different combinations of *P* and *F* parameters for each of the eight surface specimens. 576 tests have been therefore run to complete de experimental planning.

The same digitizing procedure has been used in every single test. Firstly, the spot is driven to a position that approximately matches the geometrical centre of the specimen. Taking this position as a reference or “local origin”, a 16 points mesh has been defined using a regular distribution of 8 mm spaced columns and 8 mm spaced rows. The distance between the sensor and the surface has been calculates for every point in the mesh under each of the 72 *P* and *F* combinations, starting with a (P5:F500) combination and ending with a (P60:F3000) one. This procedure has been executed for each of the 8 specimens described above.

Measurements for every single point have been obtained statically as the sensor was completely steady during measurement. Up to 100 readings for the distance between sensor and surface (γ) have been successively obtained. The representative value for the distance ($\overline{\gamma}$) has been subsequently calculated as the average value for these 100 readings. Additionally, the standard deviation of this parameter for a p point ($\sigma_{\gamma P}$) has been calculated and registered. Finally, the average signal-to-noise ratio (SNR_P) for a particular point has also been registered. As the

XYZ position of the sensor was also known for each measurement, the value of the $\bar{\gamma}$ parameter has allowed for establishing the XYZ position of the digitized point, using the appropriate calibration (Fernández et al. 2010). Following this procedure a preliminary 3D representation of the flat machined surface has been obtained for each specimen.

2.5. Data filtering

The data obtained during the digitizing process have been later processed and filtered to remove low-quality information. Firstly, measurements that have been obtained from a low-quality signal have been removed. According to the criterion given by the manufacturer, high quality measurements must provide SNR values over 50%. Secondly, the Total parameter (an indicator calculated by the sensor that is proportional to the area limited by the signal envelope) must provide values in the range of 1200 to 16000, according to recommendation of the manufacturer. After applying these filters, a number of points may be removed due to poor quality.

Once the original pointcloud contains only high-quality points, it has to be determined if it provides a good coverage of the surface of the specimen. In this work, the requirement of a minimum 90% of high quality points has been applied to guarantee the best coverage. Those combinations of *P* and *F* values providing more than 90% high quality points have been considered as high quality combinations (*HQC*).

2.6. Quality Indicators (QI)

Four *QI* have been used in this study. The first one (n) is the total number of high quality points. This indicator ranges from 0 when there have been no valid points in a particular test run, to 16 when all measured points have been considered as high-quality points. The second indicator (SNR) is the average value of all the SNR_P values within a particular point cloud, and it is related to the quality of the signal. The third indicator (σ_γ) is the average value of the $\sigma_{\gamma P}$ values for a particular point cloud, and it is related to the stability of the measurement. Finally, the forth indicator (δ_f) is the difference between the flatness value, as calculated using the digitized point cloud, and a reference value calculated using a contact touch-probe on the same CMM. The index δ_f provides information about how trustable is the virtual representation of the surface.

3. Results and discussion

3.1. Suitability of surface digitizing

Tests have been carried out following the initial planning and the resulting information has been grouped for analysis. Work has firstly focused on suitability of surface digitizing. This concept is related to a good surface coverage based on the digitized point clouds, so it can be analysed through the percentage of *P* and *F* combinations that can be considered as *HQC*. The graph on Fig. 3 represents this percentage for the different specimens.

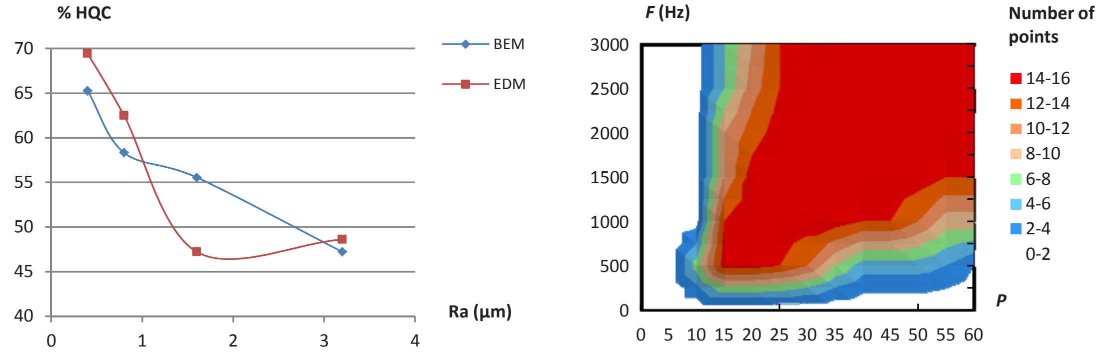


Fig. 3. Percentage of High Quality Combinations of *P* and *F* as a function of theoretical *Ra* and manufacturing process (left) and distribution of the number of valid points for the BEM, Ra=3.2 µm surface (right)

According to these results, the 34CrMo4 steel can be easily digitized, as *HQC* percentage is always higher than 45%. This means that, within the limits of the experimentation, *P* and *F* values can be properly adjusted in order to obtain an almost complete pointcloud from the digitizing process.

As a general rule, *HQC* percentage drops when the roughness parameter *Ra* increases. Nevertheless, the EDM 1.6 µm *Ra* specimen and the EDM 3.2 µm *Ra* specimen behaviours do not strictly follow this rule. Fig. 3 also shows an example of the distribution of the n quality index among the test limits for the BEM 3.2 µm *Ra* specimen.

3.2. Suitability of quality indicators

Once the analysis is limited to the *HQC*, research for a unique recommendation for *P* and *F* values has focused on simultaneous optimization of three indexes: *SNR*, σ_γ and δ_f. Achieving this objective implies finding a combination of *P* and *F* which maximizes *SNR* while simultaneously minimizes σ_γ and δ_f.

In an ideal situation, this optimal combination shall be established once for a particular material (34CrMo4 steel for present work) and will provide high quality results for different roughness levels or manufacturing processes. Following this objective, the average values for each of mentioned indicators (*SNR*, σ_γ and δ_f) have been calculated for every single combination of *P* and *F* values, taking into account both influence factors (roughness and manufacturing process). The distribution of the average values can be observed in Fig. 4.

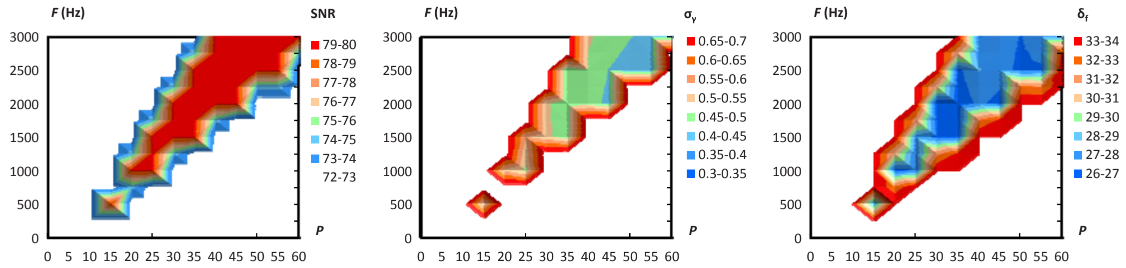


Fig. 4. Distribution of average values for *SNR* (left), σ_γ (centre) and δ_f (right) considering all the tested combinations of process and surface roughness

According to this data, it can be assumed that a (P55:F2500) configuration should be recommended when digitizing 34CrMo4 steel surfaces. An average 96.9% of valid points should be obtained within all possible combinations of process and roughness tested in present work. Values for the average *SNR* (79.55%) and the average σ_γ (0.405 µm) are optimal for this combination, while the average δ_f (26.81 µm) is only 2.7% worse than the optimal value (26.11 µm, obtained using a P55 and F2000 combination).

QI values have been calculated individually for each test specimen using this global recommendation, and they had been denoted as $Q_{I(\mathrm{P55,F2500})}$. Later they have been compared with specific *QI* optimal values ($Q_{I(op)}$) calculated using local recommendations, as is to say: using recommendations based on specific surface characteristics. These two values have been used for stabilising the percentage difference between quality results using global recommendation and local recommendation (Δ_{QI}). This indicator provides estimation for the loss of quality:

$$\Delta_{QI} = \frac{\left|QI_{(55,2500)} - QI_{op}\right|}{QI_{op}} \cdot 100 \tag{2}$$

The Δ_{QI} values (Table 2) show that using the global recommendation for *P* and *F* values causes no significant differences when compared to the optimal *SNR* values, regardless of the type of surface. On the other hand, results for σ_γ and δ_f are clearly more significant.

Table 2. Percentage difference between quality results for $QI_{(55,2500)}$

	Δ_{SNR} (%)		Δ_{σ_γ} (%)		Δ_{δ_f} (%)	
Ra (theoretical) (μm)	**BEM**	**EDM**	**BEM**	**EDM**	**BEM**	**EDM**
0.4	0.12	0.07	41.07	17.45	67.26	26.49
0.8	0.35	0.04	19.99	29.24	12.56	74.77
1.6	0.34	0.03	19.40	12.04	18.64	16.76
3.2	0.26	0.12	10.15	72.82	57.25	5.74
Average	*0.27*	*0.06*	*22.65*	*32.88*	*38.92*	30.94

While Δ_{SNR} values reaches a 0.35% maximum for the BEM process (*Ra*=0.8 μm) and a 0.12% maximum for the EDM process (*Ra*=3.2 μm), an average 22.65% $\Delta_{\sigma\gamma}$ has been calculated for the BEM surfaces and a 32.88% for the EDM ones. Finally, $\Delta_{\sigma\gamma}$ shows the worst averaged percentage among *QI* for the BEM surfaces (38.92%). To achieve a better comprehension of these results, the case of the EDM 3.2 μm *Ra* specimen can be analyzed (Fig. 5). Using global (P55:F2500) recommendation, a 0.75 μm value is obtained for the σ_γ indicator. However, using local (P55:F3000) recommendation, σ_γ shall be reduced to 0.43 μm. If the BEM 0.4 μm *Ra* specimen is considered (Fig. 5), a 12.71 μm value for the δ_f indicator is obtained, while this value could be reduced to a 7.60 μm (P15:F1000) minimum.

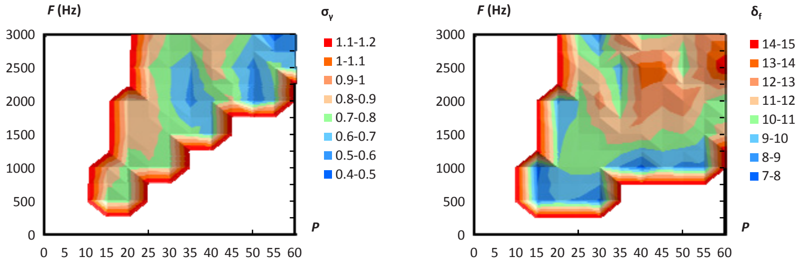


Fig. 5. Distribution of σ_γ for EDM 3.2 Ra surface (left) and δ_f for BEM 0.4 Ra surface (right)

Therefore, it can be concluded that the objective of providing one single recommendation for a particular material cannot be properly achieved. Actually, this recommendation should be established taking into account material surface characteristics. It must be highlighted that this conclusion shall not be so clear if the analysis had been limited to the *SNR* indicator.

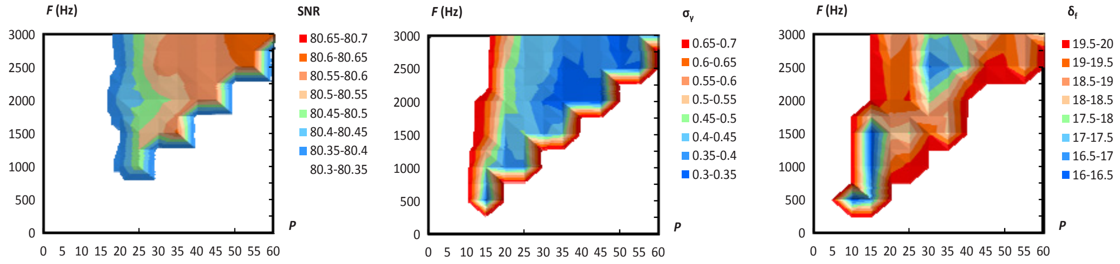


Fig. 6. Distribution of *SNR* (left), σ_γ (centre) and δ_f (right) for EDM 1.6 Ra surface

Once this conclusion was established, focus has turned to evaluate if the *QI* reach optimal values for a similar *P* and *F* configuration values, as it had happened with global recommendations. The analysis has shown that there is not a good correlation for the *QI* behaviour when they are calculated for a particular surface. To support this assessment, graphics in Fig. 6 show how EDM 1.6 µm *Ra* surface provides an 80.64% maximum using (P50: F3000), but optimal value for σ_γ (a 0.29 µm minimum) has to be obtained using a (P45:F2000) combination. Finally a 16.03 µm δ_f minimum value is obtained using a (P10: F500) combination.

As a result, a single recommendation for *P* and *F* values shall not simultaneously optimize the considered *QI*. *SNR* has been traditionally used as a trustable *QI* due to is simplicity, as it is directly provided by the sensor as a complementary data for each single measurement. Nevertheless, present work has shown that, even when *SNR* has to be used to reject low-quality points, it is not useful for establishing which digitizing conditions (*P* and *F*) shall be used for a particular surface. In fact, if the *SNR* variation is calculated among the HQC for all the test runs in present work, a 0.15% standard deviation will be obtained. This means that *SNR* values are similar among the HQC so this quality indicator is not suitable for establishing which the optimal recommendation should be.

On the other hand, averaged value for the σ_γ standard deviation among the HQC represents a 32.6% of the minimum value for each surface. Finally, averaged value for the δ_f standard deviation represents a 13.4% of the correspondent minimum value. This results show that a more complex indicator, with higher sensibility than *SNR* can be defined and used for calculating a *P* and *F* optimal combination.

4. Conclusions

Several assessments can be done after previous analysis:

34CrMo4 steel surfaces can be properly digitized using conoscopic holography, although a wide range of *P* and *F* combinations shall provide a 90% of minimum valid points and can be considered as HQC.

Although *SNR* can be used for selecting combinations of *P* and *F* which provide good surface coverage, it must be considered a poor quality indicator for establishing optimal digitizing conditions due to the low significance of its standard deviation among the whole range of HQC. Both σ_γ and δ_f indicators have clearly more significance. Moreover, it can be established that there is not a straight relation between optimal digitizing conditions for the proposed quality indicators. Future work should be focused on selecting or building a proper quality indicator, aiming on reliability of surface representation instead of signal quality or measurement stability.

Although a recommendation for *P* and *F* values can be calculated by considering the average behaviour of the indicators for different processes and roughness levels, it has been proved that this recommendation would lead to huge quality differences from optimal levels for a particular combination of roughness and manufacturing process.

The results suggest that an optimal combination of *P* and *F* cannot be obtained for this material without considering manufacturing process and surface roughness. Following this, we have concluded that optimal digitizing conditions must be determined for each single type of surface.

In future works, aims will be paid on analysing whether a correlation can be established between actual roughness values and the quality of the measured distance values in order to improve reliability of surface representation.

Acknowledgements

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