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Inspection System for Benchmarking of Perceived and Technical Characteristics of Surfaces/ Système d'inspection pour benchmarking des caractéristiques perçues et techniques de surfaces

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Résumé. La perception haptique des textures est un outil important dans l'évaluation des produits tels que les smartphones, les automobiles, les appareils de cuisine, etc. Les entreprises qui réussissent visent donc à concevoir activement l'impression haptique de leurs produits aux préférences haptiques de leurs clients. Pour cela il faut des informations quant à la façon le client perçoit des surfaces de produits et comment ces surfaces peuvent être caractérisés techniquement. L'impression haptique perçue d'un objet peut être estimée à l'aide des études humaines; les caractéristiques techniques, quant à elles, peuvent être mesurées. Cependant, dans la plupart des cas, la corrélation directe entre la perception humaine et les mesures techniques n'est pas statistiquement significative. Par conséquence l'impression haptique perçu ne peut pas être simplement dérivée des mesures bien connus. Il reste à analyser, si des mesures alternatives peuvent fournir une caractérisation plus adéquate de surfaces en termes de leur impression haptique perçue. Pour permettre une estimation plus efficace de l'impression perçue d'un objet, un système d'inspection automatique est présenté. Ce système est constitué d'un robot qui conduit un capteur biomimétique de la société Syntouch. Le sensor fournit un signal de vibration au cours du déplacement sur une surface. Cette publication présente les résultats d'une étude pour mettre en corrélation les signaux du capteur avec les perceptions humaines de la rugosité de surfaces différentes. Les résultats sont mis en comparaison à une corrélation entre des valeurs de rugosité standardisées et la rugosité perçue.

Abstract. Haptic perception of texture is an important tool in the evaluation of products such as smartphones, automobiles, kitchen appliances etc. Successful companies thus aim at actively designing the haptic impression of their products to the haptic preferences of their customers. However doing so requires information as to how comparable product surfaces are perceived by the customer and how these surfaces can be characterized technically. The perceived haptic impression of an object can be estimated using human studies, whereas its technical characteristics can be measured. However, direct correlation between perceived and standard measurements often shows poor significance, thus perceived haptic impression can not be simply derived from standard measurements. It remains to be analysed, if alternative measurements can provide a more significant characterization of surfaces in terms of their perceived haptic impression. To allow a more efficient estimation of the perceived impression of an object, an automatic inspection system is presented. This system consists of a force controlled robot driving a biomimetic sensor by the company Syntouch, providing a vibration signal during traverse over a surface. The paper presents results of a study to correlate the sensor signals to the perceived roughness of different surfaces evaluated by human subjects and set this in comparison to a correlation between standard roughness values and the perceived roughness.

1 INTRODUCTION

Product quality is an ambiguous construct. ISO 9000 defines quality as the "degree to which a set of inherent characteristics fulfils requirements" [1]. These requirements are always set by the customer, and thus the customer is also the one who evaluates these "inherent characteristics" to determine the quality of a product. Humans use their own "sensory mechanisms" of vision, touch, smell etc. to evaluate a product. [2] Consequently, important inherent characteristics of a product from the customers perspective are those which he is able to perceive. These characteristics, e.g. the perceived texture of a surface or the sound of a button, can be subsumed under the term "Perceived Quality" (PQ). [3][4]

The haptic impression evoked by product surfaces is one of the major factors of a products perceived quality. [5] To reach a final specification of 1-2 surfaces for a specific design element, up to 100.000 available surface materials have to be reduced through product design. [6]

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In order to specify the customer requirements regarding perceived quality characteristics, it is necessary to define criteria which comprise the sensory impression from the customers perspective, characterize them for possible product designs and bring these into correlation to objectively measureable (production-) specifications (materials can be e.g. specified through physical, mechanical, thermal, acoustic tactile attributes and more). [6][7] Characterization can be done using subject based so called "sensory studies". The profile method [8] originating in the food industry and derivate of this method [9] are effective methods for sensory studies.

In the sense of the topic of "Soft metrology" the characterization of the perceived quality parameters can be seen as an original "measurement. This is in accordance to the definition of the term "measurement" by Bortz & Döring, who define measurement as the "assignment of values to objects", thus not limiting it to the extraction of standardized values. [10] In terms of this extended definition, the quantification of descriptors in sensory studies and alternative technical procedures can also be considered to be measurement procedures.

However, measurement of perceived quality using customer studies is quite resource consuming due to the subjective nature of human perception and the subjects difficulty of exactly characterizing their own perception. This usually results in large sample sizes. Technical systems which have been referenced to perceived quality characteristics could serve as an alternative or extension to these studies. To keep the costs for measurements using these technical systems low, they should be able to evaluate the actual product and not be confined to laboratory samples.

To allow an efficient estimation of the perceived haptic quality of products, i.e. a more efficient product benchmarking regarding their impression on human haptic perception, an automatic inspection system, is currently under development. This system uses a novel biomimetic sensor by the company Syntouch which mimics the functionality of the human haptic system. Ideally, the system should provide data which indicates the human haptic perception and the technical roughness of the surface. In this paper, the system will be presented and as a first step. Consequently, the ability to predict the perceived roughness of surfaces assessed by subjects in a sensory study from the system's sensor signals will be evaluated and compared to standard values of roughness metrology.

2 STATE OF RESEARCH

Research on technical systems which are specifically designed to enable estimation of perceived roughness is scarce. On the other hand, a lot of research was dedicated towards examining the correlation between perceived roughness and technical roughness measurements. These approaches will be discussed first, to show the potential, and the limits of the inspection system presented in this paper.

Chen et al. examined the correlation between touch perception of textures and a standardized physical surface measurement of packaging materials. Within a study, subjects were asked to rate 37 different packaging surfaces on six continuous semantic scales (e.g. warm-cold and smooth-rough) and to state their hedonic impression of the surface (like, not sure, do not like). Within the results, a coefficient of correlation of $R^2 \sim 0.6$ was found between the technical roughness (R_a) and perceived roughness. Values of R_a for the individual surfaces lie between 0.05 µm and 13.02 µm. [11]

Tiest & Kappers analysed a specific technical system towards its ability to estimate the similarity or dissimilarity of surfaces in terms of their perceived roughness. They used a so called "Universal Surface Tester" by the company Innowep to obtain height profiles of 124 different surfaces. These were used to determine intensities (power) at four discrete bands of spatial frequency, which were evaluated as influence factors for perceived roughness. In addition, the surfaces were evaluated by 20 subjects regarding their perceived roughness. Results show significant correlation between the distances between perceived roughness of the surfaces and the artificial (non standardized) roughness measurement. No statement is made towards the standardized technical roughness of each surface. [12]

Hollins & Bensmaia discussed the relationship between perceived roughness and measurable surface characteristics. They conclude, that for relatively coarse structures, the spatial periods, i.e. the distance from one surface elevation to the next one is a good measurable indicator of perceived roughness (spatial period >0.2 mm). To analyze how finer surfaces (spatial period <0.2 mm) can be characterized, they conducted a study in which surfaces are moved against the index finger of subjects and the subjects stated which one from a pair of surfaces they perceived as rougher. This difference in perception is argued by the so called "Duplex-theory of texture perception". [13] Results showed that vibrations induced on the skin during this traverse represent surface roughness on the fine level. This results confirm the hypothesis, that fine surface texture characterization is enabled through the activation of the so called Pacinian corpuscles during movement of the skin against a surface. [14][15]

None of the presented results depicts a solution which provides a very good correlation between the measured variables and the perceived haptic characteristics. Furthermore, none of the approaches features a system able to do an efficient benchmarking of the perceived haptic parameters of products. Thus, further efforts are necessary to improve the technical "measurement" of the perceived haptic parameters of a product, especially its perceived roughness. Because different measurement procedures were used in the presented approaches with promising result, information or signal fusion (compare [16]) could be a way of realizing a very high level of predictability of perceived haptic characteristics with a technical measurement system.

Measurement of roughness

Different technical measurement procedures have been developed to determine the roughness of a surface initially to ensure that machined parts like bearings or shafts meet technical roughness specifications. Standard roughness values can be obtained with existing technical procedures through a profile (2D, according to the standard ISO 4287 [17]) or a surface (3D, according to ISO 25178 [18]), depending on the requirements of the application. Optical or tactile Profilometers are used to record the profile of a surface. Structured light 3D-scanners allow two- and three-dimensional roughness measurements. These allow to record the roughness of fields of up to 8 mm x 6 mm in one measurement. The resolution of established roughness measurement procedures ranges from 4 µm up to 0,1 µm. [19]

A measure according to measurement standards (e.g. the DIN 1319) has to be a physically defined value. In analogy to the extended definition of “measurement” by Bortz & Dörin mentioned in the introduction, the quantification of descriptors, bet it through human studies or technical procedures which record data from surfaces, can be seen as measurement procedures, as well. Existing approaches to “measure” the perceived roughness through technical measurements are discussed consequently.

3 APPLIED METHODOLOGY

Components of the inspection system

To realize a system for the characterization of product surfaces in a benchmarking scenario, four technical requirements have been determined:

1. To allow fast and easy use, the system should be able to reach every surface of a product, not being limited to the evaluation of plain lab samples of surfaces. This way, costs related to the set-up of each benchmarked surface would be kept to a minimum, as also mentioned in section 1.
2. The system should allow the use of different sensors to tap as many potential sources of information as possible, and eventually enable sensor fusion as proposed in section 2.
3. The resolution of the systems measurements should be sufficient. One twentieth of the tolerance is often mentioned in literature as a guideline for resolution. [20] As the tolerance, the differences in the measurement which evoke no difference in perception can be defined.
4. Measurements should be accurate (i.e. repeatable). In respect to the MSA 4, the standard deviation due to measurement repetitions should be less than 30 % than the deviation between parts.
5. Measurements should be valid in respect to the perceived quality of products characterized using the measurements, i.e. correlation between the measured values and the predicted perceived characteristic should ideally be >90 %.

To fulfil the requirement regarding flexibility (1 & 2), the system is based on a six-axis industrial robot (ABB IRB 120). This robot allows sufficient motion-wise flexibility to reproduce the complex *exploratory movements* [21] performed by humans for the characterization of haptic product characteristics. The robot is shown in Figure 1.

Figure 1: Haptic inspection system. 1) BioTac biomimetic sensor 2) ATI FT-Gamma force sensor

To allow tactile measurements of surfaces with defined force (allowing repeatability of a movement in regard to requirement 4), a six-axis force/torque sensor (ATI Gamma) is mounted to the arm of the robot. For the use of haptic measurement, a novel biomimetic sensor (Syntouch BioTac) is under evaluation. The sensor is mounted to the force/torque sensor and contains a set of different modalities which perform in analogy to human haptic perception. The BioTac is shaped like a human finger and comprises 36 micro-sensors under an artificial skin which has a fingerprint-like structure. The sensors are able to detect static pressure, micro-vibrating pressure temperatures, temperature gradients and the displacement of the artificial skin. The BioTac thus tries to mimic different functionalities of the human mechanoreceptor system. Its developer Fishel was able to show, that it is possible to discriminate different textures with very high accuracy (>99 %) using the BioTac (requirement 4)[22]. However, the sensors accuracy coupled with a robot as the movement providing device, remains to be evaluated since the robot will probably generate significant noise in the vibration signal due to acceleration an deceleration.

Applied methodology

To examine the capabilities of the system in its current state, three hypotheses were made and evaluated consequently:

Hypothesis 1: Vibration is not directly related to standard units of roughness measurement, i.e. the two measurement methods are not interchangeable which would make the vibratory measurement somewhat redundant.

Hypothesis 2: Perceived roughness of surfaces is related to the intensity of vibration as measured by the vibration sensor modality of the BioTac.

Hypothesis 3: Differences in perceived roughness between surfaces can not be sufficiently explained by differences in technical roughness characteristic of said surfaces.

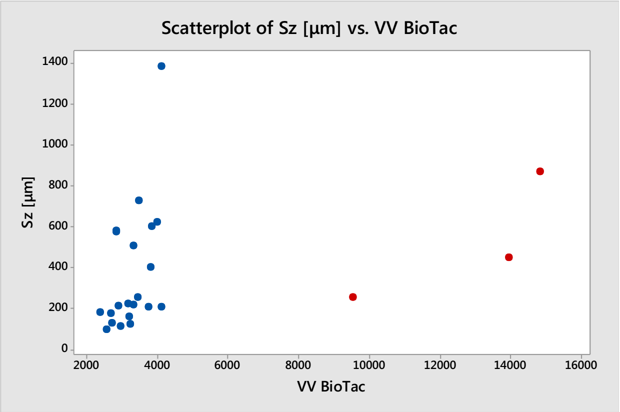

Figure 3: Scatterplot highlighting three data points of distinctly high *VV* values.

To evaluate hypotheses 2 & 3, an experimental study was conducted. Two sets of 12 different surfaces each were used for this study, one consisting mostly of sand-paper and similar technical surfaces and one consisting mainly of leather and artificial leather, i.e. consumer oriented surfaces. All surfaces were at least 70 mm x 50 mm in size and mounted to a stiff block. The experiment consisted of three steps:

Step 1: The 24 surfaces were measured using conventional metrology regarding the standardized measurement parameters. A 3D-profilometer (Alicona InfiniteFocus) was used for this purpose. All relevant 2D-parameters for the profile (*P*), waviness (*W*) and roughness (*R*) and all relevant 3D-surface-parameters (*S*) were generated in this step.

Step 2: A sensory study was conducted in analogy to the sensory evaluation method developed by Falk et al. [9]. Within the study, 56 subjects were asked to evaluate the dissimilarity of each surface compared to every other surface in terms of their perceived roughness, on a seven point scale (1 indicating a very small and 7 a very high dissimilarity). This methodology was chosen to enable MDS of the perceived roughness later on.

Step 3: The surfaces were evaluated using the BioTac sensor mounted to the ABB robot. In accordance to the stimulation frequency of the Pacinian corpuscles [23], the vibration signal of the BioTac was filtered using a band-pass-filter for frequencies between 60-700 Hz. To obtain the signal data for each surface, a standard exploration movement was executed with the sensor traversing over each surface with a defined pressure of 0.5 N vertically to the surface and a simple linear movement of the sensor between two predefined points using a speed of 20 mm/s. Force control during traverse of the sensor was not used, to prevent the force control from influencing the vibration signal. This way, about 4000 data points were generated from each surface, as sampling rate for each surface was 2200 Hz. Each surface was measured 3 times using these settings to determine the repeatability of the vibration signal. After filtering, the variance was generated from the individual data points as a measure for the intensity of vibration. For readability, the vibration variance value will be indicated as *VV* in the following.

Data analysis

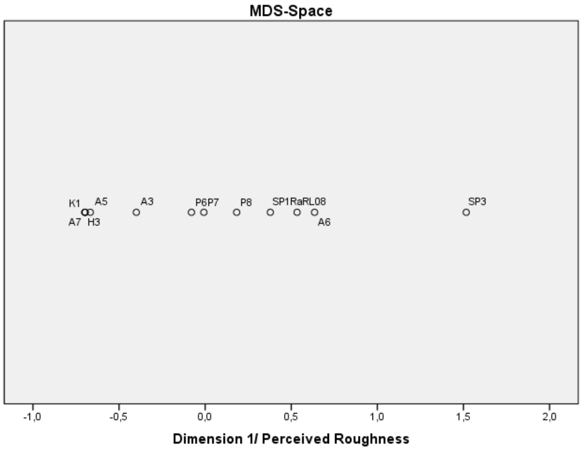

Figure 2 : One dimensional MDS scale showing the distances between the surfaces of set 1 from the subjects dissimilarity evaluations. Higher values indicate higher

The data extracted through the standardized measurements, the sensory study and the BioTac measurements were analyzed using the software solutions SPSS, Minitab and Excel. Data analysis was done in two major directions.

First, correlation was determined between the standard roughness values and the VV to evaluate whether the measurement of vibration can indicate certain standard measurements and to which degree the two measurement approaches are interchangeable. Data from the study (step 2) was analyzed using nonmetric multidimensional scaling (MDS) to identify the number of dimensions necessary to sufficiently describe the differences in perceived roughness within the study results (so called “mapping”). To do so, the data from the pairwise comparisons was evaluated by creating a dissimilarity matrix from the medians of the dissimilarity ratings by the subjects participating in the study. Using these medians, the number of dimensions which describes the dataset with a sufficiently low S-stress value was determined (compare [12]). Consequently, the *VV*, the R_{Sm} and S_z values for sets 1 and 2 were evaluated in their predictability of the study results, i.e. to one of the prime dimensions of the MDS space using methods of multivariate analysis.

In addition, repeatability of the vibration measurements was determined. Prior pre-experiments indicated, that finer surfaces in terms of the spatial width also resulted in a smaller error between repetitions. ANOVA was done to compare the *VV* between the three repetitions of vibration measurements to the variance of the means of the *VV* between the surfaces.

4 RESULTS AND DISCUSSION

To evaluate hypothesis 1, linear correlation was determined for all 24 surfaces combined between all standard roughness value and the mean vibration variance value. Spearman’s rho was used for this matter, since data was not normal distributed due to the manual (not random) selection of surfaces and there were some outliers in the data. From the examined 23 standard values, 8 correlated with p<5 % to the *VV* measured using the BioTac-sensor. The standard value S_z, which refers to the maximum elevation found in the surface texture showed the highest coefficient of regression with a value of $r_s = 0.577$. However three distinct data points are visible in the scatterplot shown in Figure 2 between S_z and VV which produced significantly higher vibrations than the other 21 data points. Exclusion of these points did not significantly alter the result, even reducing the resulting coefficient of regression to $r_s = 0.552$.

These results give confirmation to hypothesis 1. Correlation between the VV and standard roughness values is fairly small, meaning that the vibration induced by a surface during traverse can indeed not be accurately modeled by one of the popular standard roughness values. Thus, the two approaches of measurement are not interchangeable.

To examine hypothesis 2 and 3, the MDS approach described in chapter 3 was applied. MDS-stress analysis for both surface sets showed, that one-dimensional models were sufficient to obtain S-stress values smaller than 0.1, i.e. values of 0.016 and 0.054 respectively. This serves as an indicator, that subjects were sufficiently able to evaluate the surfaces solely on their perceived roughness, and not mixing it with other haptic factors (like e.g. hard-/softness). Figure 3 shows the resulting one dimensional scale of the first set, which was thus assumed to be the perceived roughness of the study subjects. The resulting MDS scale was correlated to the VV, the R_{Sm}, the S_z and the $R_z$values of the respective surfaces. For set 1, the highest correlation was indeed given between the VV and the MDS scale resulting in a Spearman's rho of $r_s = 0.79$. One specific surface deviated highly from the MDS For the second set, the highest correlation was determined to be between the MDS scale and the R_{Sm} value, resulting in $r_s = 0.92$. all the values of the two sets are displayed in Table 1.

Table 1. Spearman's rho correlation coefficients and R²(adjusted) values of linear correlation between the MDS scales of the two surface sets and the technical measurements

Parameter	**MDS scale set 1**		**MDS scale set 2**	
	Spearman's rho	Linear R²(adj)	Spearman's rho	Linear R²(adj)
VV (Vibration)	0.785	62 %	0.510	28.3 %
Rz	0.673	72.2 %	0.343	0 %
RSm	0.718	50.8 %	0.916	80.6 %
Sz	0.715	27.2 %	0.853	47.7 %

The results indicate that perceived roughness can be estimated based on technical measurements. No clear measurement however stands out as the one which fits the perceived roughness data best in all cases. Hypothesis 2 can be confirmed, by showing that there is significant correlation between the measured VV and the perceived roughness scales developed using MDS. To evaluate the predictability of the perceived roughness, linear correlation analysis was performed. Figure 4 shows the results of a regression fit between the scale of set 1 and the VV, also showing one significant outlier of less VV than expected by the surfaces perceived roughness (the surface is an artificial rubber surface with a criss-cross structure). The resulting value of R²(adjusted)=62 % shows slight positive correlation between the VV and the perceived roughness scale.

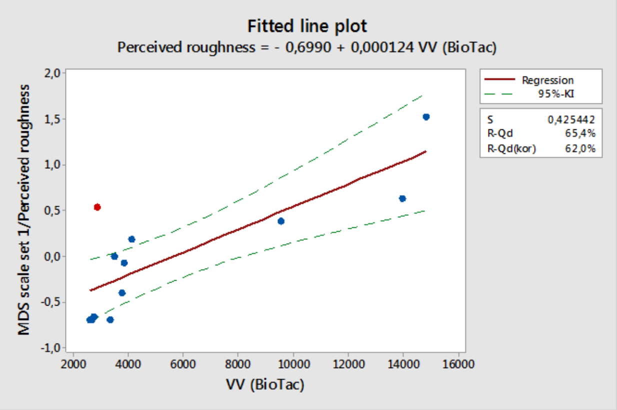

Figure 4. Fitted line plot of a linear regression between the MDS roughness scale from surface set 1 and the VV values. The red dot indicates a significant outlier.

To evaluate hypothesis 3, it was necessary to look at the individual data values. The data shows, that neither of the three standard roughness values is able to correctly predict the surfaces which were perceived to be the roughest and the smoothest by the study subjects in the first set. In the second set however, the surfaces that were perceived to be smoothest and roughest also were determined to have the lowest and highest R_{Sm} and S_z values respectively. Linear correlation between the R_{Sm} value and the MDS scale values of both sets resulted in coefficients of determination of R²(adjusted)=50.8 % for the first surface set and R²(adjusted)=80.6 % for the second set. The combined R²-values of linear correlations between the MDS scales and the other standard roughness values were on average lower than those of the R_{Sm} (see Table 1). As a result, hypothesis 3 can not be dismissed, since no standard measurements can model the perceived roughness obtained through the sensory study to a sufficient degree for all evaluated surfaces.

Repeatability of vibration measurements

For the first set of surfaces, variance due to repetitions amounted to 35 % of the total observed variance whereas values above 30 % are generally seen as critical (see e.g. [24]) . This value can be considered as high, already indicating that further work is necessary to make the vibration measurement procedure more stable and reduce noise factors influencing the measurement. For the second set of surfaces, variance due to repetitions was 10 % of total observed variance, however observed variance in the second set was much higher (factor 10) than in the first set.

5 CONCLUSION AND OUTLOOK

In the paper, a system was presented which aims at providing efficient and reliable haptic benchmarks of products, i.e. predicting the perceived haptic impression of the products on the customer. To realize this task, the system uses a force controlled robot to guide a novel biomimetic sensor over a surface. The sensor which was originally developed by Fishel et al. mimics critical mechanoreceptors of the human finger. Furthermore the paper presents the results of a study in which 56 subjects evaluated the perceived roughness of two sets of surfaces using a pairwise comparison. Perceived roughness scales were determined using multidimensional scaling and for each surface used in the study a vibration signal was acquired from the novel sensor and standard roughness values were determined using an optical profilometer. Using correlation and linear regression analysis it was evaluated, whether the vibration signal or standard values could effectively predict the perceived roughness. It was shown, that none of the determined measurements was able to predict the perceived roughness differences of both sets of surfaces to a high degree (R^2>70 %). The vibration signal did show a value of R^2=62 % for one set of the surfaces, for the other one however the value was just 28.3 %. Due to the high variance between repeated vibration measurements of the same surface, i.e. poor repeatability, these values could be significantly improved by enhancing signal repeatability.

Correlation analysis was also performed between the vibration signal and the standard values and showed, that the vibration signal is not directly correlated to any of the 23 standard roughness values considered in this study. It was concluded, that the vibration signal indeed provides a discrete characterization of surface, compared to standard values and at this time no conclusion can be drawn from the vibration measurements to certain areas of standard values.

In conclusion these results show, that the capability of the system to deliver robust measurements using the BioTac sensor has to be further improved. Especially, the influence of the robot movement on the vibration signal detected by the BioTac has to be minimized, whereas a frequency analysis might be applicable to detect the characteristic frequencies induced by the robot movement to ex post remove them from the vibration spectrum. However the results indicate that the signal data might be able to provide an accurate prediction of perceived haptic product parameters, such as the perceived roughness, once signal repeatability is improved.

To serve the purpose of the system of providing an efficient possibility for haptic benchmarking, several aspects are under development besides the systems capability of providing accurate measurements. To enhance the usability and efficiency of the system, self-optimizing capabilities will be implemented during the course of further development. Thus, the system will ultimately be usable even by users with relatively little or no specific knowledge of robotics. Also, additional sensors will be integrated into the system to evaluate the possibility of information/sensor fusing.

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