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Author(s)	Hwang, Jihong; Lee, Jooho
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FABRICATION OF DETERMINISTIC AND RANDOM SURFACES USING 3-D PRINITNG TECHNOLOGY FOR PSYCHOPHYSICAL STUDIES OF ROUGHNESS PERCEPTION

JIHONG HWANG
Dept. of Mechanical System Design Eng., Seoul Nat'l Univ. of Sci. & Tech.
272 Gongneung-ro, Nowon-gu, Seoul, 139-743, South Korea

JOOHO LEE
Dept. of Product Design & Manufacturing Eng., Seoul Nat'l Univ. of Sci. & Tech.
272 Gongneung-ro, Nowon-gu, Seoul, 139-743, South Korea

ABSTRACT: For psychophysical studies of roughness perception, it is vital of importance to efficiently fabricate the sample surfaces that have different levels of physical roughness. In this context, the present study seeks to develop an efficient way of fabricating such sample surfaces using 3-D printing technology, which consists surface modeling, 3-D printing and measurement. Reliability of this method is ensured by conducting a psychophysical experiment with the samples fabricated using the developed method and comparing the results with those of the previous studies.

INTRODUCTION

Since mobile devices such as smart phone, touch pad and portable play station have been used routinely in our daily lives, the sense of touch has been of great interest. This is because, in many cases, information delivery for these devices is made through touch, and users' satisfaction is substantially affected by the sense of touch (Chen et al. (2007)). There are many aspects of a surface that can be sensed by touch, for example, coldness/warmness, hardness/softness, friction, etc. Among these, surface roughness is one of the factors to be considered critical when designing or manufacturing the outer surfaces of a product due to its significant role in improving product quality and users' satisfaction.

As a result, psychophysical studies of roughness perception have been made more intensively in recent years (Hwang & Hwang (2009), Kawasegia et al. (2013)). Psychophysics is "the analysis of perceptual processes by studying the effect on a subject's experience or behavior of systematically varying the properties of a stimulus along one or more physical dimensions" (Bruce et al. (1997)). That is, the psychophysical study of roughness perception quantitatively investigates the relationship between surface roughness as a stimulus and its perception. To carry out this study it is important to have a capability of varying surface roughness in a controlled manner, and in most cases this is enabled by having a set of the surface samples which have different levels of physical roughness.

The surfaces which have been of interest in psychophysical studies can be classified into two subcategories: deterministic and random. Deterministic surfaces consist of periodically placed, well-defined, simple forms such as triangle, hemisphere, pyramid or truncated cone. Such deterministic surfaces have been artificially made using conventional machining on metal (Lederman & Taylor (1972)), bulk-micro machining on silicone (Lamb, 1983) and injection

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molding on plastics (Kawasegia et al. (2013)). However, these fabrication methods are not efficient in cost and time albeit the shapes are relatively simple. This resulted in employment of sand papers or Emory cloths as the surface samples for psychophysical studies, which has a limit in tightly controlling the roughness factors.

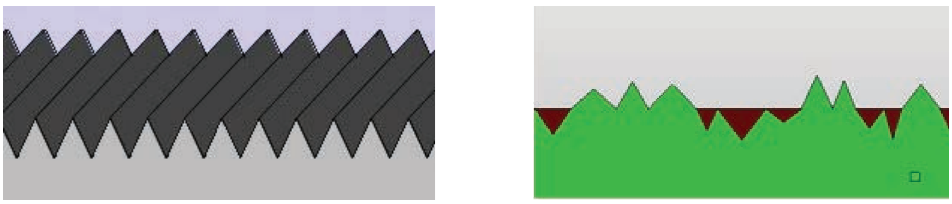
Random surfaces, on the other hand, consist of peaks and valleys whose height and lateral space are randomly given. That is, the random surfaces are stochastic and usually characterized using terms from probability. Although the random surfaces are better representation of natural surfaces, it has been considered difficult to fabricate them in a controlled manner. This has limited employment of the random surfaces for psychophysical studies of roughness perception. Only a few studies have been made on the random surfaces by collecting lots of natural sample surfaces and then sorting them by each of roughness factors (Tiest & Kapper (2006, 2007)). However, the interaction of height and spatial roughness factors and the effects of material properties such as stiffness and friction could not be isolated in these studies.

Therefore, it is meaningful to develop an efficient way of fabricating surface samples whichever are deterministic or random because it would facilitate the psychophysical study of roughness perception. In this context, the present study seeks to develop a method for fabricating surface samples using 3-D printing technology which are beneficial when fabricating the parts that have complexity and variation in their shapes and are small in volume. This consists of 3 steps; surface modeling, 3-D printing and measurement. Reliability of this method is ensured by conducting a psychophysical experiment with the samples fabricated using the developed method and comparing the results with those of the previous studies.

FABRICATION OF SURFACE SAMPLES

Modeling of surfaces

Deterministic surfaces can be easily modeled using 3-D CAD software because there shapes are simple and the values of their geometric attributes are deterministically given. For an example, a 3-D cad model of the surface consisting of periodically spaced, identical triangles is shown in Figure 1. (a). Unlike deterministic surfaces, however, random surfaces cannot be modeled by 3-D CAD software easily. Therefore, in the present study, models for the random surfaces were created using MATLAB. In these models, the random surfaces consist of a series of random peaks and valleys. Such surfaces could be modeled by making a random queue of peaks and valleys whose heights and widths were randomly given, and then placing them along a reference line as illustrated in Figure 2. Then, these random surface models were built into the STL file format (*.stl) that could be read by a rapid prototyping machine.



(a) Deterministic (b) Random

Figure 1. Models of deterministic and random surfaces

3-D printing

The surface samples were printed using a poly-jet 3-D printer (model no.: EDEN 330, manufacturer: Objet Geometries Ltd.) which has the resolution of 600dpi in *x* and *y* directions and 1600dpi in *z* direction (16μm). 40 deterministic and 40 random surface samples were built using the conditions shown in Table 1. All the samples have the size of 40mm (width) × 20mm (height) × 5mm (thickness).

Table 1. Conditions used for fabricating the deterministic and random surfaces

	Height [mm]	Width [mm]
Deterministic	0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0	0.8, 1.2, 1.6, 2.0
Random	0.1-0.2, 0.1-0.4, 0.2-0.6, 0.3-0.8, 0.6-1.0, 0.6-1.2, 0.8-1.4, 0.8-1.6, 1.0-1.8, 1.0-2.0	0.4-1.2, 0.6-1.8, 0.8-2.4, 1.0-3.0

Measurement

The surface shapes of the fabricated samples are not exactly same as the modeled shapes due to limited accuracy of the 3-D printing machine and shrinkage of the sample material during curing. Therefore, surface roughness measurement was conducted for the fabricated sample surfaces. The measurement was made by extracting the surface profiles from the sample images taken from the side. This method allowed us to overcome the limits of a commercial surface profilometer found when measuring steep peeks or valleys – short measurement range, jamming of the probe in the narrow valleys for the contact type profilers, and scattering of light on the steep peaks and valleys for the noncontact type profilers. For validation of this method, roughness was measured for the standard sample surfaces whose roughness could be measured by a commercial surface profilometer. The roughness values obtained by both methods were correlated well as shown in Figure 2., which indicates that the measurement by image analysis is reliable enough. Figure 3. shows measurement result obtained for all the sample surfaces fabricated.

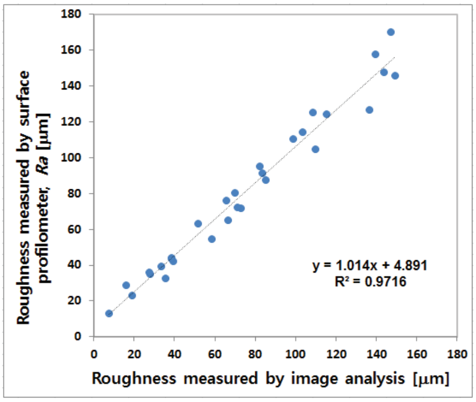


Figure 2. Correlation between the roughness values measured by the surface profiler and the image analysis

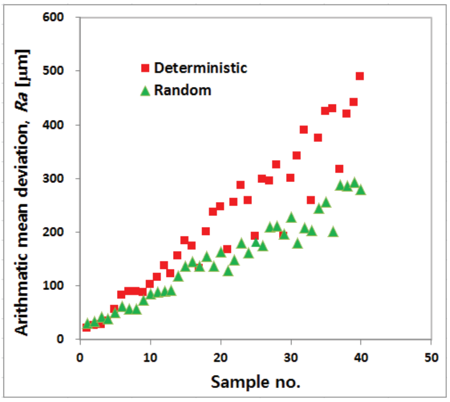


Figure 3. Distribution of surface roughness for the samples

PSYCHOPHYSICAL EXPERIMENT

Method

A psychophysical experiment was conducted to investigate the correlation between the surface roughness parameters and perceived roughness. Perceived roughness was measured by having people touch the sample surfaces with their index fingers and recording the intensity of perceived roughness using their own scale. Prior to the measurement, each of the participants had time to touch a couple of the sample surfaces – highly smooth one and highly rough one, and to set up their own scale. As a result, the scales used for quantifying the perceived roughness were varied with the participants.

In total, 20 people participated in this measurement. The participants were university students in the age of 21-29, and the numbers of male and female participants were even. During the measurement, the participants wore headsets and blindfolds to avoid audial and visual interference, respectively. Whenever the participants felt tired, they were given five minutes of rest before the measurement was resumed. The measurement was made only once for each of the participants without any repetition.

Analysis & Result

For each of the participants, Pearson's correlation coefficients between the surface roughness parameters and the perceived roughness were calculated using the SPSS software. The surface roughness parameters considered in this analysis included *Ra* (arithmetical mean deviation of the profile), *Ry* (maximum height of the profile), *Rz* (ten point height of irregularities), *Sm* (mean spacing of the profile irregularities) and *S* (mean spacing of local peaks of the profile). Among these, *Ra*, *Ry* and *Rz* belong to the amplitude parameters while *Sm* and *S* belong to the spacing parameters.

Pearson's correlation coefficients averaged over the 20 participants are shown in Table 2 for the surface roughness parameters considered here. In the table, it is noted that, for the random surfaces, the amplitude parameters (*Ra*, *Ry* and *Rz*) have relatively strong correlation with perceived roughness (Pearson's correlation coefficient larger than 0.8) while the spacing parameters (*Sm* and *S*) have weak correlation (Pearson's correlation coefficient smaller than 0.5). This is contrasted to those for the deterministic surface, in which the space parameters (*Sm* and *S*) have relatively strong correlation with perceived roughness (Pearson's correlation coefficient larger than 0.7).

Table 2. Correlation between the standard physical surface roughness parameters and perceived roughness

		Ra	Ry	Rz	Sm	S
Pearson's Correlation Coefficient	Deterministic	0.883	0.897	0.806	0.411	0.264
	Random	0.699	0.654	0.661	0.719	0.718

DISCUSSION & CONCLUSION

Through the psychophysical experiment carried out for the deterministic surfaces consisting of linear gratings, Lawrence et al. (2007) found that the spacing between two adjacent features had strong correlation with perceived roughness. In their study, the surface samples were made by photoengraving a polymer. Similar results were also observed in the studies that employed the metal surfaces made by conventional machining and the silicone surfaces made by bulk-micromachining for the samples. In the present study, it was found that, for the deterministic surfaces, the space parameters (*Sm* and *S*) have relatively strong correlation with perceived roughness. Although the space parameters are not exactly same as the spacing between two adjacent features, their correlation should be quite high. Therefore, the results found for the deterministic surfaces in the present study are in consistency with those from the previous studies obtained for the deterministic surfaces. Likewise, the results found for the random surfaces in the present study are in good agreement with the previous study in which the strong correlation between the amplitude parameters (*Ra*, *Ry* and *Rz*) and perceived roughness was observed. These all indicate that the surface samples fabricated by 3-D printing technology can be reliably used for psychophysical studies of roughness perception.

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