https://doi.org/10.2352/issn.2169-2629.2021.29.105

Influence of procedural noise on the glossiness of 2.5D printed patches

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Abstract

Perlin noise, a type of procedural noise, was used for the design of elevation files for 2.5D printing. This printing method uses elevation data from a height map to create physical relief by superimposing layers of ink. In this experiment, the grayscale values of noise functions were used as elevation values to build different surface structures in UV curable ink by 2.5D printing. Printed samples with varying levels of Perlin noise were created and their reflectance properties were studied by measuring the values of specular gloss. The roughness and specular gloss of the printed surfaces were effectively influenced when varying the persistence and octaves of the noise functions. The aim of implementing the procedural approach to a high-resolution printing method has been to explore the reflectance properties of custom noise functions when transferred to the physical realm. This might contribute to better understand the effect of surface structure on the appearance of materials. Potentially, this approach will enable the use of relief printing to produce structures with a more natural appearance and a desired gloss value by using a low-cost computing process.

Introduction

The surface topological features influence how light reflects on a certain material and how it is perceived. The scale, distribution and periodicity of morphologic features contribute to the overall shape, waviness and roughness of the surface. Roughness ranges from millimeters down to nanometers, and can be studied as features of different scale superimposed on each other [1]. Although there are other contributions to gloss [2], features with wavelength in the visible spectra range interact with visible light and this has an effect on the optical properties of the surface, such as specular gloss[3]. Specular gloss refers to the ratio of the reflected light to the incident light on the surface where both incident and reflected angles are equally placed on the opposite sides of the surface normal[4-5].

Roughness height distribution (or amplitude wave form), and the lateral spacing (or wavelength) are values used to define the surface topology. Increasing the amplitude of roughness increases the spreading of reflected light, thus increasing diffuse scattering and reducing gloss. The lateral distribution of topographical heights, or wavelength, has also been shown to affect light scattering and specular gloss [1]. Surface properties larger than microscopic roughness are called bumpiness, meso-texture [6] or waviness [7]. Visual judgements of bumpiness and glossiness are not independent of each other. Gloss can affect the perception of global shape by making surfaces appear more curved, or convex surfaces concave. Similarly, shape can affect judgments of surface reflectance, making textured surfaces appear glossier [8]. In their study on the perception of gloss and texture Ho et al. [6] modelled how 3D texture or bumpiness and specularity (glossiness) affect the perception of the other. They found that observers made judgments of “bumpiness” and “glossiness” of surfaces that varied in both surface texture and specularity. This study, made in computer-based simulation, has become a reference for other works addressing the influence of surface geometry on perceived specularity using physical samples. In Baar et al. [8] physical samples of surfaces varying in surface gloss and texture levels were created by a 2.5D printing system, confirming by psychophysical experiments a slight influence of surface texture on the perception of surface glossiness.

Elevated printing or 2.5D printing

2.5D printing adds relief (elevation, height) to a 2D print. Canon Elevated Printing Technology uses UV curable ink to create 2.5D prints. Elevation is created by superimposing successive UV ink layers, which are 4 – 40µm thick. After each layer the ink is cured, resulting in a built-up elevation. One or more ink colors can be printed, although by default all colors are used resulting in blackish elevation layers. The built-up elevation is covered with a white layer and on top of it a color layer is printed to create a full color print. Canon Touchstone is an application for Canon Arizona flatbed printers. It offers Elevated Printing up to 1mm in height. Within Canon Production Printing facilities in Venlo, the Netherlands, printing up to 5mm or higher is possible on prototype printers. Input file formats to create Elevated Prints are 3D mesh files (like .STL, .OBJ) or a height map, which is a 16bit grayscale image where the intensity values correspond to height values. A Canon raster imaging processor converts color and heightmap files into slices, containing elevation, white and color data, that can be printed automatically.

By simultaneously producing color and morphological features, such as texture and relief, this technology can mimic certain material appearances for applications in the reproduction of fine art and ancient artefacts, and in the manufacture of appealing advertising. It is not straightforward, however, to reproduce any kind of surface to a convincing level for the eye. Glossiness and translucency are appearance properties that depend on the material’s physical composition. Therefore, there are intrinsic limitations to the range of appearances that can be rendered with UV curable ink by controlling the variables of the printing method. The type of substrate and inks, the print mode, drying time, etc. are printing variables that affect the final appearance. Baar et al.[4] investigated how to control the printout roughness by manipulating the way the ink is deposited on a layer-by-layer basis. Local gloss variations and reflection effects were induced by changing the deposition time in between two layers of white ink and the order on which the pixels are printed. Gloss values decreased as the ink deposition time between the layers was increased, as the ink is allowed to dry out between layers. An underlying layer of white increases the gloss, whereas a more matt appearance is produced by splitting the number of pixels of a certain ink, or halftone screen, in different layers. The addition of layers of varnish is a possible measure to increase or decrease the glossiness of an inkjet relief print. Samadzadegan et al. [9] studied spatial variations of gloss in controlled areas created by varnish-halftones. Colour-samples with 13 different varnish levels were created and tested with psychophysical experiments and measurements. The relationship between perceived texture (or bumpiness) of a printout and the amount of specular reflection is perceived as gloss variations, is investigated in [8]. A series of patches was printed using an Océ 2.5D prototype printing system that had the capability of printing several types of textures in different elevations and various gloss levels by means of varnish deposition. In addition to the five gloss variations, six levels of texture were applied on surfaces named 'Bumpy' and 'Facet'. The texture of these patches was created according to the surfaces used by Ho et al. [6] and Ho et al [20] respectively, and was adjusted to fit to the dimensions of the printout (7cm x 7 cm). The facet surfaces were made by connecting triangular facets with random orientation.

Printing noise to create roughness

As an alternative to using regular geometries to create texture, we aimed to investigate how the roughness of natural materials can be introduced in the printed method, and the effect it could have on the specular gloss. We have used procedural noise as a method to generate microscopic roughness and mesoscopic texture. Noise is a random and unstructured pattern, and it is useful as a source of extensive detail without evident structure. Procedural noise functions are used in computer graphics, to add complex and intricate visual details in synthetic images through texturing. A texture obtained from a noise pattern inherits the advantages of noise: Non-periodicity, low memory cost, resolution and efficient random access [10]. The adjective procedural is used in computer science to distinguish entities that are described by program code rather than by data structures. Some applications of procedural texturing are the rendering of clouds, waves, tornadoes, rocket trails, heat ripples, incidental motion of animated characters, etc. Noise functions are implemented in off-line rendering for film production, video games, and in every major 3D computer graphics software package.

In the frequency domain, a signal is determined by specifying the amplitude and phase for every frequency. However, for unstructured patterns, such as noise, the phase is random and does not contribute useful information. Therefore, noise is often described by its power spectrum, which specifies the magnitude (squared) of each frequency and ignores the phase. The power spectrum is directly related to the autocorrelation of an image, which describes how closely related two points in an image are as a function of their distance and orientation [12]. Many tasks involving noise can be described as manipulations of the power spectrum of the noise, or spectral control. A procedural noise function is parametrized, so it can generate a class of related noise patterns rather than being limited to one fixed noise pattern. A large number of different patterns can be quickly generated by controlling the power spectrum of the noise. In image statistics and in filtering processes, 2D noise and roughness in surfaces can be studied with analog tools, such as measures related to power spectral density (PSD) [11].

The relationship between gloss and surface topography on paper was modelled by Schinichi et al. [13]. As the paper surface structure is difficult to measure and it is irregular, the authors proposed a mathematical model of paper surface topography based on procedural noise, in particular Perlin noise. To estimate the paper surface topography, they assumed surface topography as expressed as the Perlin noise. In coated paper, the gloss of paper samples increased as the power spectral density decreased overall.

Perlin noise is a kind of lattice gradient noise. It is generated by interpolating or convolving random values and/or gradients defined at the points of an integer lattice. It was introduced by Perlin in 1985 and continues to be used in research and industry [10]. Perlin noise recreates natural textures by adding up noisy functions at a range of different scales. To create a Perlin noise function, values amplitude, size, octave and persistence are required. A noise function is essentially a seeded random number generator. Seed refers to a value that is used as a starting point to calculate the noise. Changing the Seed usually changes the look of the noise without changing the look or size of its features. A single number is used to specify the amplitude of each frequency. Each noise function is twice the frequency of the previous one. The effect of those input values is the following:

- Scale: number that determines at what distance to view the noise map
- Octaves: describes the number of loops that the code is running for finer and finer detail.
- Lacunarity: number that determines how much detail is added or removed at each octave (adjusts frequency)
- Persistence: is a multiplier that determines how much each octave contributes to the overall shape, or how quickly the amplitudes diminish for each successive octave in a Perlin-noise function. The amplitude of each successive octave is equal to the product of the previous octave's amplitude and the persistence value.

Materials and methods

To investigate the dependency of the specular gloss on a noise pattern, we have generated grayscale images of Perlin noise to use them as elevation data, recalling the principle of terrain generation from height maps, common computer graphics.

The elevation data of the grayscale image is converted into physical relief in UV curable ink. For the printer's software the darkest value is the highest relief and the whitest value is zero relief.

Samples design and printing

A set of 24 patches with a different Perlin noise pattern was produced with an open source texture generator [14]. Every patch is a grayscale image of 512x512 pixels. The grayscale patches will be transferred to a physical relief according to the intensity values of each pixel. The higher areas correspond to the darker intensity values and the lower areas to the whiter values. This is opposite to a height map where higher elevation is encoded in whiter pixels. The area of each physical patch was 5x5 cm and they were placed together in a 6x4 grid, as shown in Fig 1. Two grids with different maximum heights were printed for the measurements: A) 0.75 mm and B) 1.5 mm. The maximum height is set up by the printer user in the printer software. The relief samples were manufactured with inkjet curable ink with a white surface. The variable inputs of the texture generator defining the noise output were the number of octaves (1-10), persistence (0-1) and seed (>1). The scale value was kept on 10 considering that physical dimensions are determined when printing. Table 1 shows the values used in the 24 patches.

Table 1. Number of patches in the same order as in Fig. 1 and texture generator inputs. Oc, P and S meaning octaves, persistence and seed, respectively.

Oc=10 P=.5		Oc=10 P=1		Oc=10 S=2		Oc=5 S=2	
#	S	#	S	#	P	#	P
1	1	7	1	13	0	19	0
2	2	8	2	14	0.2	20	0.2
3	4	9	4	15	0.4	21	0.4
4	10	10	10	16	0.6	22	0.6
5	20	11	20	17	0.8	23	0.8
6	100	12	100	18	1	24	1

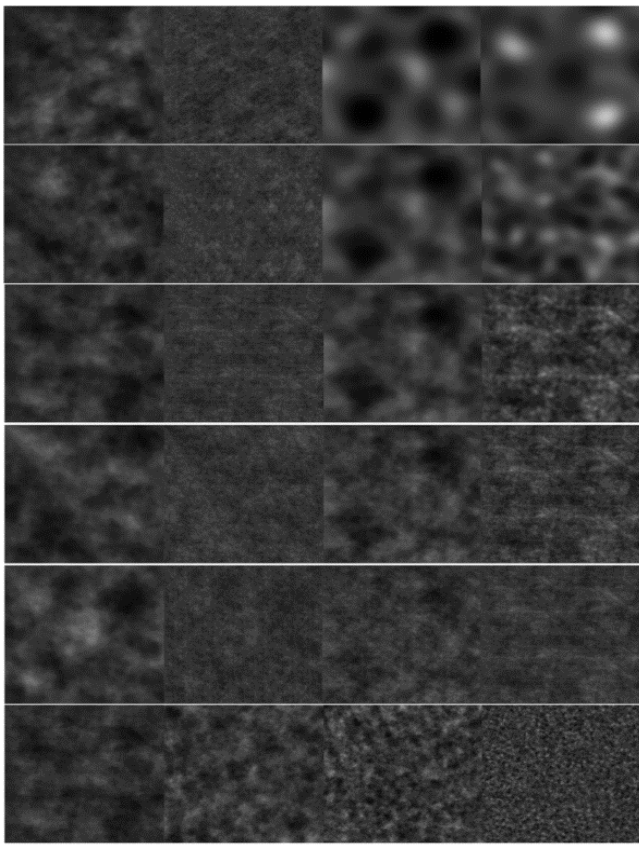

Fig 1. *Perlin noise patches. Variables shown in Table 1. Opposite to height map, where clearer areas are higher elevation, here darker areas are printed higher.*

The grayscale patches of Fig 1. were printed as relief via a Canon flatbed Arizona UV printer (Touchstone - Project Eiger) at Canon Production Printing facilities. Elevated technology is capable of printing relief in color although we have only used white ink for the relief external layers. Fig 2 shows a section of the 0.75mm relief print.

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Fig 2. *Inferior section of relief print with maximum height of 0.75 mm based on Perlin noise patches (Fig 10).*

Results

The glossiness of the samples was measured using a Canon surface reflectance analyzer RA532H, according to the standard ISO 2813 for the geometries 20° for high gloss, 60° for semi-gloss and low gloss 85°. Gloss samples are not high-gloss according to the supplier, therefore will not be considered for the analysis. The device measures specular gloss in gloss units (GU). A GU is defined in such a way that a glossy material with a refractive index of 1.567 has the value of 100 GU for any illumination angle. Usually, this glossy material is a mirror-like black glass that is used as the surface of reference [4]. Measurements are shown in Table 2 and the Fig 3-5 are graphs of gloss for the 24 patches by each angle of measurement and two levels of maximum height. Four series of 6 patches were generated by variable and fixed values as given in Table 1. Every six patches there is a tendency change in the graph which corresponds with fixed and variable values being switched.

From 1 to 6 the number of octaves and persistence is kept fixed in 10 and 0.5 respectively and the seed changes. It is expected not to have changes in the overall roughness even though the noise pattern will not be the same. From 7 to 12 octaves and persistence are 10 and 1. Seed values were varied as in 1 to 6. Likewise, no considerable variations of roughness were expected between patches, although it was not clear how a larger persistence would influence the result. From 13 to 18 octaves and seed are kept in 10 and 2 respectively and persistence is varied from 0 to 1 in intervals of 0.2. Finally, from 19 to 24, the number of octaves is reduced to 5, while seed is kept at 2. Persistence is varied from 0 to 1 in intervals of 2. It is expected that increasing persistence will increase the roughness of the Perlin noise image.

Table 2. Measurements of gloss

	.75 mm			1.5 mm		
#	20°	60°	85°	20°	60°	85°
1	2.5	16.2	12.1	2.1	12.3	9.1
2	2.5	15.6	10.3	2.2	12.8	7.1
3	2.5	15.6	12.2	2.2	12.2	9.5
4	2.4	14.1	11.2	2.0	10.9	8.0
5	2.4	14.4	9.4	1.8	8.0	4.3
6	2.1	13.3	9.9	1.9	11.6	8.2
7	1.8	10.0	6.3	1.5	6.8	3.3
8	1.8	10.4	6.0	1.4	6.2	3.3
9	1.9	11.0	6.4	1.5	6.1	3.3
10	1.9	10.5	6.0	1.4	6	2.7
11	1.9	11.3	6.3	1.4	6.1	2.8
12	1.9	11.2	6.5	1.6	7.7	3.7
13	2.8	17.9	12.6	2.6	15.3	9.2
14	2.6	16.4	11.8	1.8	9.5	8.0
15	2.6	16.6	12.1	2.3	14.1	9.9
16	2.3	14.7	9.9	2.0	10.1	6.2
17	2.0	12.4	7.6	1.6	7.7	3.6
18	1.8	9.7	4.8	1.3	5.0	1.8
19	2.8	17.9	12.6	2.2	13.3	12.1
20	2.3	14.5	10.8	2.3	13.6	9.7
21	2.2	13.1	7.8	1.6	6.8	3.9
22	1.8	9.7	5.3	1.5	5.9	2.5
23	2.0	11.9	7.0	1.6	7.5	3.9
24	1.4	6.3	2.5	1.2	3.3	0.8

From the graphs in Fig 3-5, we can observe the following:

- Changing seed value does not affect the glossiness, as it does not affect the roughness, even though the pattern is different.
- Specular gloss is generally higher when using a smaller persistence value. Increasing persistence increases the amount of detail and therefore the roughness. The surface in consequence is more matt.
- From 13 to 18 and from 19 to 24, the variable is persistence. In both segments there is an inverse relationship between persistence value and gloss.
- Surfaces with 1.5mm as a maximum height are less glossy. That means that increasing the amplitude of noise decreases the gloss around 20%

To further observe the relationship between gloss and roughness induced by persistence values, the gloss values are plotted as a function of persistence in Fig 5. Measurements here are organized in series according to the maximum height (amplitude) and the number of octaves. The tables show that the minimum gloss is obtained for a higher amplitude (1.5mm) and a higher number of octaves.

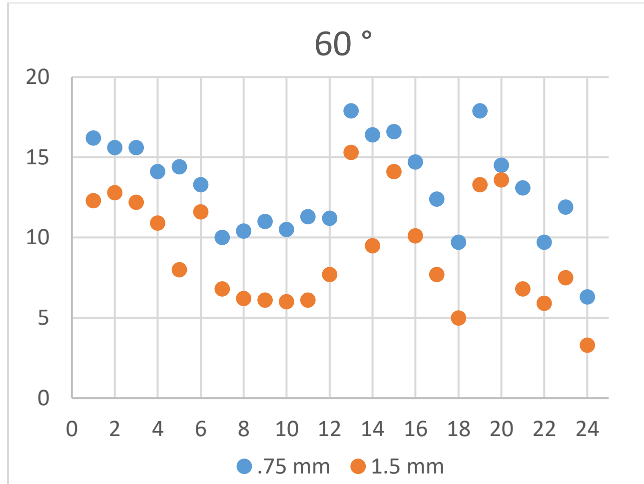

Fig 3 Specular gloss in GU measured at 60 degrees for maximum height of .75 mm and 1.5 mm

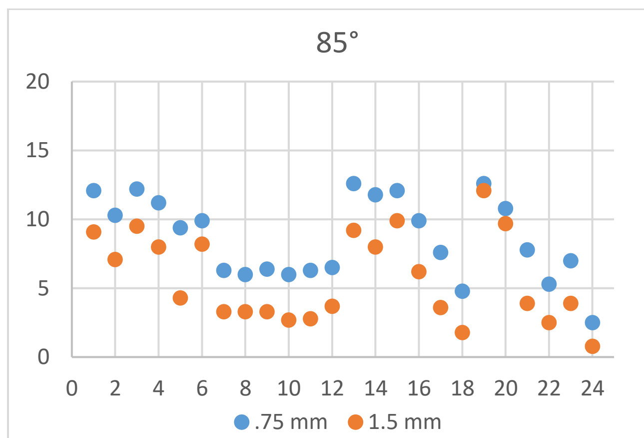

Fig 4 Specular gloss in GU at measured at 85 degrees for maximum height of .75 mm and 1.5 mm

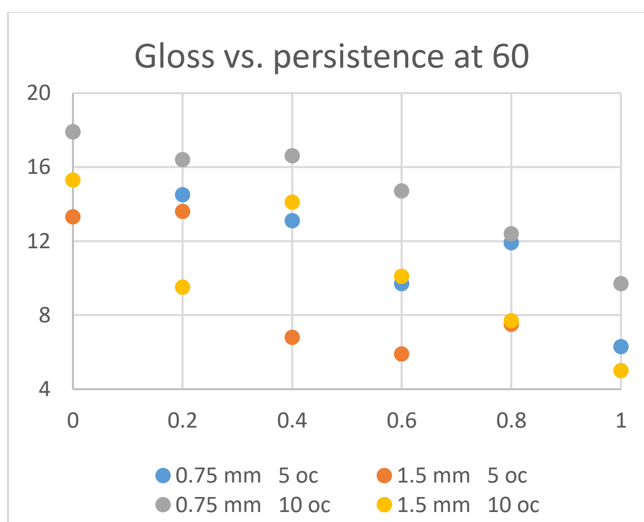

Fig 5 Gloss values in GU as a function of persistence for different maximum heights and octaves

Discussion

Even though the printed patches are surfaces made of the same material, there is a difference in roughness by visual inspection and a quantitative difference in specular gloss.

By transferring a noise pattern to a physical surface, and using the gloss as a measure to infer changes in the roughness, we have verified the effect of varying the inputs of seed, octaves and persistence. There is certainly an inverse dependency of the gloss on the amount of detail. Persistence is a multiplier that determines how quickly the amplitude diminishes for each successive octave in a Perlin noise function. The amplitude of each successive octave is equal to the product of the previous octave's amplitude and the persistence value [15]. We have verified that increasing the persistence produces "rougher" Perlin noise. It has been verified as well that such roughness is transferred as surface roughness. As the gradients in grayscale are printed as height gradients linearly, this has a contribution to the wavelength and amplitude. When printing two different maximum heights (0.75 mm and 1.5 mm) the amplitude of surface roughness influenced specular gloss, which agrees with existent literature. Previous studies have found that the gloss decreases exponentially with the roughness [19].

The results have led us to identify how to improve the experiment and which measurements would help exploit the principle verified here, which is controlling the glossiness of 2.5D prints by implementing texturing by procedural noise. Such measurements are the root mean square height of the surface area and the power spectral density (PSD)[16] in both grayscale patches and printed surface, in order to have a link between surface structure and its reflectance properties[17]. Moreover, from the PSD curve of the surface roughness, characteristic topographic features, and the overall magnitude of the micro-roughness profile can be derived [18]. Research in evolutionary-art and rendered images has found that measures related to PSD are useful to understand how synthetic images differ from natural images, considering for instance the dependency of power spectra on the spatial frequency [11-12]. Likewise, this could help improve the appearance of synthetic printed images by elevated printing.

The samples used in this experiment depended on the number of pixels and the dimensions of the print chosen by the user. To incorporate statistical measurements that are unbiased, future work will consist in measuring the topography in different scales and reconstructing an accurate PSD of the surface in order to determine a workflow that connects the spectral analysis of the noise with a PSD curve and finally with characteristic gloss values.

Conclusions

Roughness influences how light scatters on a surface and it has an effect on its reflectance properties. It was possible to generate different levels of surface roughness in relief prints based on grayscale patches of procedural noise that were used as elevation files. The roughness of the printed surface was effectively influenced when varying a Perlin noise function. By modifying the spatial frequency and the amplitude of the noise, the roughness of the surface changed, which can be inferred from the measurements of specular gloss. An inverse dependency of the gloss on the persistence of the noise was observed, as the persistence increases the level of detail of the noise pattern. The maximum height of the prints had an influence on the amplitude of the roughness, which reduced considerably the gloss of the samples. When the noise is transferred to relief on a printed material the dimension is arbitrary. The dimensions we used were in a range that had a measurable effect in the specular reflection, however, if the scale is too big the noise would influence the waviness or the shape of the surface more than the roughness (microscopic). Previous studies have found that the gloss decreases exponentially with the roughness. It is convenient for future work to involve topographic measurements with physical dimensions as well as spatial image statistics.

Acknowledgements

This research was funded with the support of EPSRC grant EP/R011761/1, ApPEARS Appearance Printing European Advanced Printing School European Union's Horizon 2020 research and innovation programme under the MSCA ITN-ETN grant agreement No. 814158 and Research England Expanding Excellence in England Fund 2019/22: Centre for Fine Print Research.

We thank Clemens Weijkamp from Canon Production Printing for reviewing this paper and for providing the samples.

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Donatela Šarić is also a member of the Appearance Printing European Advance Research School (ApPEARS). She has a Bachelor's degree and a Master's degree in Graphic Technology from the University of Zagreb, Croatia. She is interested in the field of image processing and color reproduction and her current research in Fogra is on the implementation of gloss in the 5-channel appearance space within a colour-managed workflow.

Susanne Klein is a physicist by training and has lived and worked in the UK since 1995, first as a Royal Society Research Associate at the University of Bristol, and then as a Senior Research Scientist at Hewlett Packard Labs Bristol. She has been appointed an EPSRC Manufacturing Fellowship at the Centre for Fine Print Research starting January 2018. She is working on the reinvention of old printing technologies, such as Woodburytype and Lippmann photograph.

Carinna Parraman's understanding of 2.5D printing has evolved through her training in in fine art print-making. She is Professor of Design Colour and Printing and Director at the Centre for Fine Print Research, and has in-depth knowledge of traditional colour mixing, colour printing and photomechanical printing processes. She collaborates with many different sectors including industry, heritage and fine-art print.