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Psychophysical Insights into Anisotropic Highlights of 3D Printed Objects

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Abstract

3D printing has been extensively used for over two decades by various practitioners and professionals in the industry. This technique, which involves adding material from melted filament layer by layer based on CAD model geometry, imparts a unique appearance to the printed objects. The layering structure generates specific directional reflectance patterns on printed surfaces, leading to anisotropic highlights. Due to slight inaccuracies in the printing setup, the appearance of individual layers is not seamless and exhibits sparkle-like effects along the highlight. In this paper, we conducted a psychophysical experiment to analyze human perception of the printed objects, focusing on the intensity and width of the anisotropic highlights. We discovered that the contrast near the highlights and the variability of pixel intensities along the highlights are highly correlated with human ratings. Lastly, we present a straightforward method utilizing these computational features to enhance the visualization of 3D printed objects.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer graphics]: Graphics systems and interfaces—Perception I.3.3 [Computer graphics]: Image manipulation—Texturing

1. Introduction

Fused Deposition Modeling (FDM) 3D printed objects have a distinctive appearance due to their layering structure. The typical layer thickness in FDM printing is 0.1 mm, resulting in contours that are clearly distinguishable to the naked eye, especially in highlighted areas. Due to the directional structure of the printing layers, the objects do not exhibit a smooth appearance or localized specular highlights. Instead, they display spatially continuous anisotropic highlights, typically oriented perpendicular to the printing build angle that defines the layering structure [TJ14]. Fig. 1 shows visibility of these effects on FDM printed objects using different filament types. In this paper, we analyze the visual aspects of printed surfaces. Initially, we conducted a psychophysical experiment to analyze human perception of (1) the intensity and (2) the width of the anisotropic highlights. Subsequently, we tested several computational features that predict human judgments based on the experiment's findings.

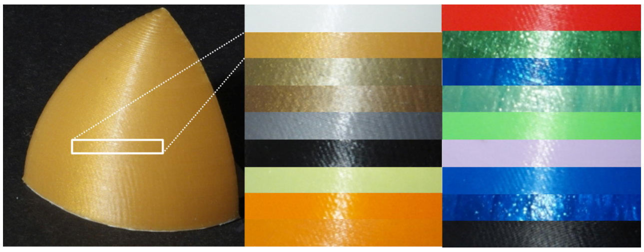

Figure 1: *An illustration of the variety of anisotropic highlights on a 3D object printed using different filaments.*

2. Related Work

3D printing has been widely adopted for over a decade and utilized by various practitioners and professionals in industry. The most frequently used 3D printing process is a material extrusion technique called fused deposition modeling, creating a 3D object by adding material from melted filament, layer-by-layer based on CAD model geometry [TJ14]. Clark et al. [CFG21] studied effect of printing parameters e.g. printer nozzle size, print layer height, and print orientation on optical properties of prints like the refractive indices, attenuation coefficients, and level of birefringence of various plastic filaments. Filip et al. [FKV19] studied effects of azimuthally-dependent behavior due to structural elements of 3D printed flat specimens. They simulate two types of structure-based anisotropic effects, which are related to directional principles found in real-world materials. For each type, a set of test surfaces with controlled anisotropy level is printed and assessed in a psychophysical study to identify a perceptual scale of anisotropy. This is a follow-up to [FKV22], analyzing and predicting the perceived reflective translucency of 3D-printed planar surfaces using the same set of material filaments.

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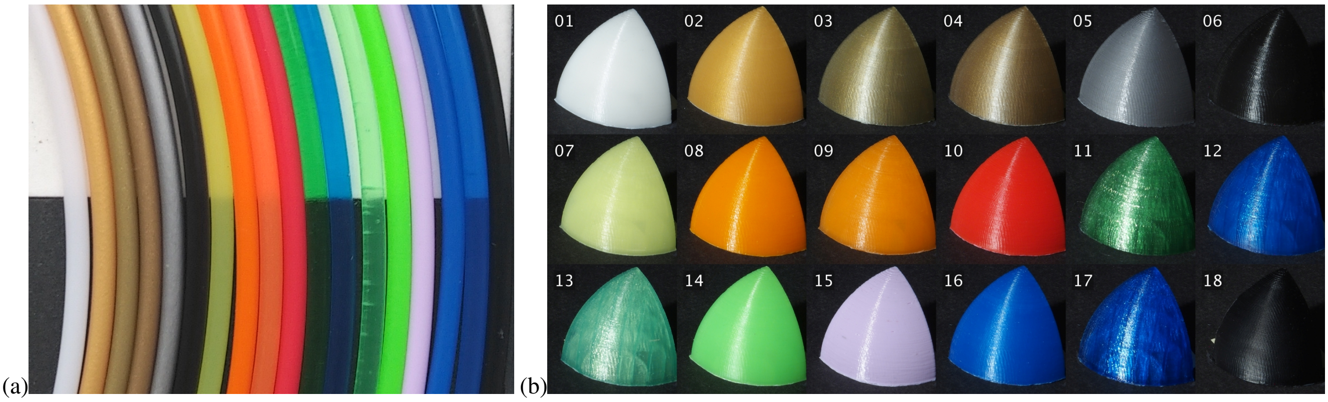

Figure 2: *(a) Tested eighteen filaments and (b) respective 3D printed objects used as stimuli in the study.*

3. Psychophysical analysis of anisotropic highlights

Test samples – For our experiments, we utilized 3D printing filaments made from fifteen PLA (Polylactic acid), two PET (Polyethylene terephthalate) samples (numbers 13 and 17), and one ABS (Acrylonitrile butadiene styrene) sample (number 18) each with a diameter of 1.7 mm, as shown in Fig. 2-a. For the purposes of our psychophysical analysis, eighteen quarter-spheres with a diameter of 40 mm were printed, as shown in Fig. 2-b.

Perceived anisotropy intensity and width – In our online study, observers viewed images of all samples as shown in Figure 2-b and evaluated (1) the intensity and (2) the width of the anisotropic highlight using an eleven-point Likert-like scale. On this scale, 0 represents the lowest and 10 the highest intensity/width. These ratings are intended to reflect only the range of materials within the study; thus, the highest ratings correspond to the material with the highest intensity/width observed in our study, rather than in the real world. We adopted this design approach because it is prevalent in image and video experiment methodologies [Kee03].

In two separate experiments, participants rated the intensity and width of the anisotropic highlights for each material. To facilitate the perceptual scaling tasks, each stimulus presented all the samples under evaluation. A total of 53 and 27 participants took part in the respective experiments. Since these experiments were conducted online, we do not have information about the participants' ages. However, it is known that the participants were naive regarding the purpose of the experiment. All participants were instructed to take part in the study only if they had normal or corrected-to-normal visual acuity.

Prior to data analysis, we checked for outliers and assessed agreement among participants. First, we performed outlier rejection by removing values that differed from the mean participant responses by more than 5 scale points. In total, 56 outliers were identified, representing 3.9% of the 1428 values recorded in the study. Next, we evaluated the agreement of participants' responses using Krippendorff's α [HK07] – a statistical measure that generalizes several known statistics to quantify agreement among independent observers. α of 1 indicates perfect agreement, while a value of 0 indicates none. The obtained α values of 0.558 and 0.680 indicate a decent level of agreement among the participants. We also analyzed the significance of differences between sample means by conducting hypotheses testing with repeated-measures ANOVA. The obtained p-values of 0.00004 and 0.046 demonstrate reasonable statistical significance.

To gain insight into typical participants' responses, we computed the mean opinion score, which is the average rating across all participants. The mean opinion scores for the tested materials, ranging from 0 to 10, are shown in Figure 3-a,b in blue (materials are arranged row-wise). The error bars in the graph represent standard error values. We observed a high similarity between the measured intensities and widths of anisotropic highlights. The Pearson correlation coefficient between the results of the two experiments is R=0.830. Interestingly, the materials perceived to have the highest highlight intensity and width include those containing metallic pigments (materials 03 and 04) and highly translucent materials (11, 12, 13, and 17).

4. Predicting perceived values

Computational prediction of the perceived intensity and width of anisotropic highlights plays a key role in the development of visually accurate rendering model for FDM printed surfaces. Therefore, we utilized image data from the original stimuli (see Fig. 2-b). As the highlight narrows down and angles toward the pole of the sphere, we applied an image dewarping based affine transformation using four points (shown as red dots in Fig. 4-a). The resulting image used for our analysis is shown in Fig. 4-b. To specify the highlight width, we initially tested the full width at half maximum (FWHM) on the mean intensity across rows of the warped image, referred to as highlight profiles (see Fig.5-a, where colors correspond to filament colors). However, this yielded very low correlations with the perceptual studies, specifically R_I=-0.147 for intensity and R_W=0.145 for width (see Fig.3-c).

Next, we tested several features related to image contrast, capturing the relationship between the actual change in a physical stimulus and the perceived change. The best results were obtained for Weber contrast [WC], which involves computing the difference between the highlight value and the value on the surface approximately 15 degrees aside from the highlight divided by the highlight

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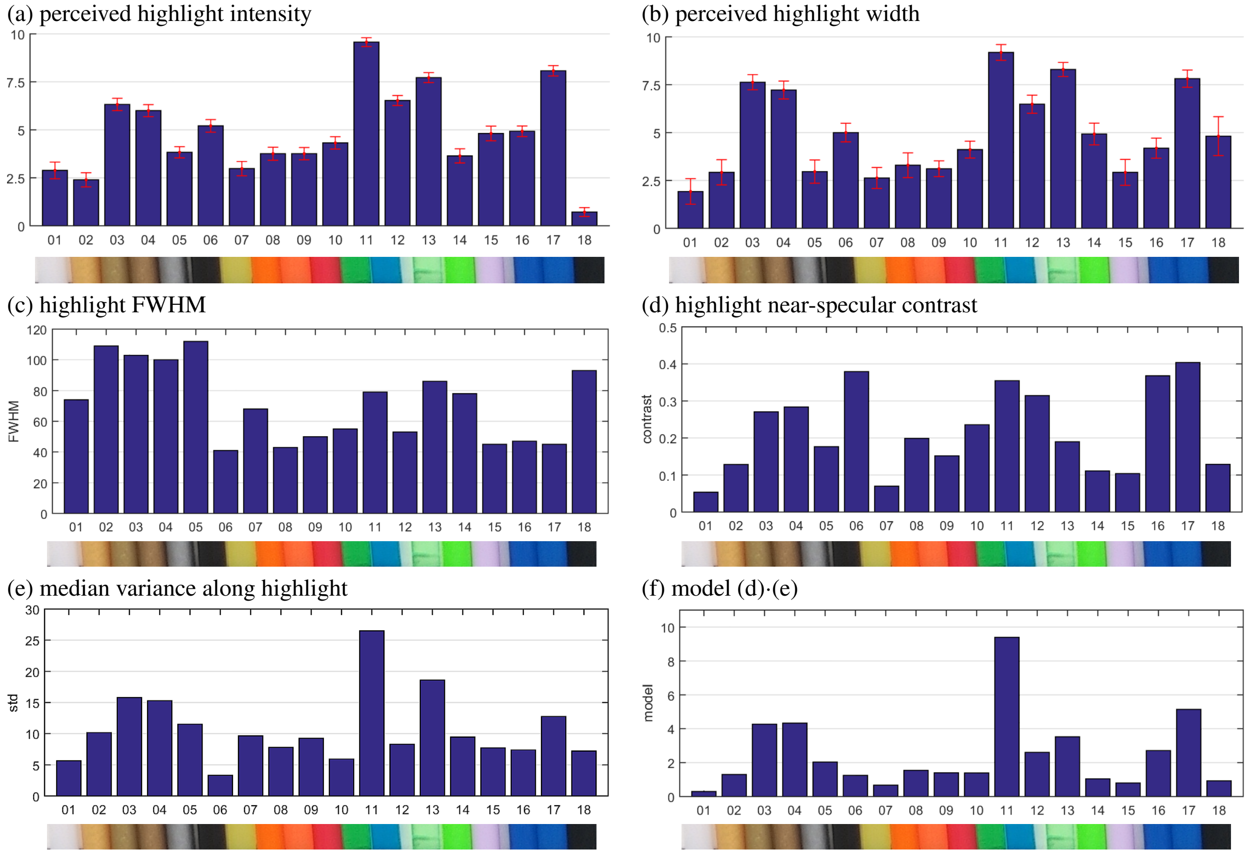

Figure 3: *The perceived highlight (a) intensity and (b) width obtained from the experiment. Tested features used for experimental data modeling: (c) full width at half maximum, (d) near-specular contrast, (e) median intensity variance along the highlight, and (f) a combination of (d)·(e).*

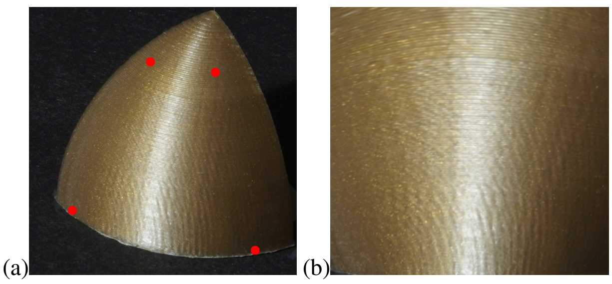

Figure 4: *(a) Stimuli image and (b) its warping to obtain image with vertically aligned highlight for image processing analysis.*

value. The near highlight and highlight values for our tested samples are shown in Fig.5-a as intersections of dashed outlines with the profile curves. The difference values for individual samples are shown as horizontal outlines on the right side of the plot. This feature, shown in Fig.3-d, has a relatively high correlation with the experiments, R_I=0.710 for intensity and R_W=0.659 for width. This suggests that near-highlight intensity contrast might significantly impact the perceived highlight intensity.

Eventually, we tested whether the intensity variation due to the structure of filament layers correlates with highlight intensity perception. We tested different approaches: the standard deviation over the entire highlighted part, and the mean value of the standard deviation along and perpendicular to the highlights. Although all variants yielded correlation values over 0.7, the standard deviation of intensities across rows of the warped image, obtained as a median value across all columns, yielded the best results. These deviations are shown in Fig.5-b, with their median values indicated as horizontal outlines on the right side of the plot. This feature, shown in Fig.3-e, closely matches the experimental results, resulting in Pearson correlations of R_I=0.701 for intensity and R_W=0.743 for width. This suggests that intensity variations might significantly impact the perceived highlight width.

Finally, a multiplicative combination of near-highlight intensity contrast and intensity variation, as shown in Fig. 3-f, yielded the highest correlation with the experimental data, with R_I=0.846 for intensity and R_W=0.839 for width, effectively explaining over 70% of the perceived intensity and width of anisotropic highlights.

Predictive rendering – To enhance the realism and perceived intensity of anisotropic highlights in 3D printed object visualizations,

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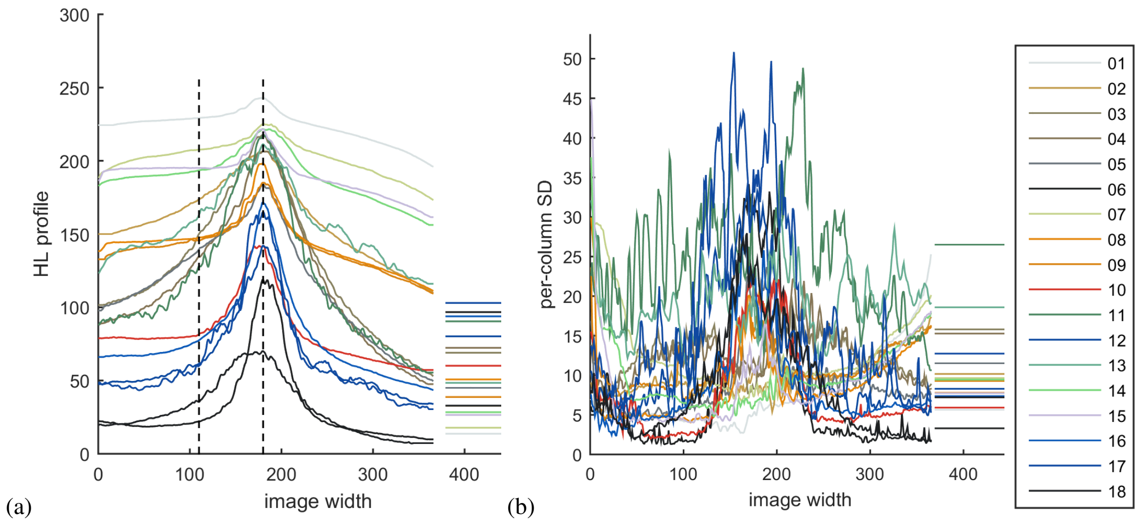

Figure 5: *Intensity profiles of highlight (a) and standard deviation for individual columns od the warped images (b). The colors of the outlines correspond to the samples' colors.*

one can introduce appropriate variability in intensity across the layers during the rendering stage. Fig. 6 demonstrates how combining near-highlight contrast and variance enhance the perceived realism of visualizations of 3D printed hemisphere of the diameter 20 mm in the Mitsuba renderer. We used an additive noise texture scaled by the local highlight contrast and the standard deviation across 3D print layered structure at different positions along the anisotropic highlight.

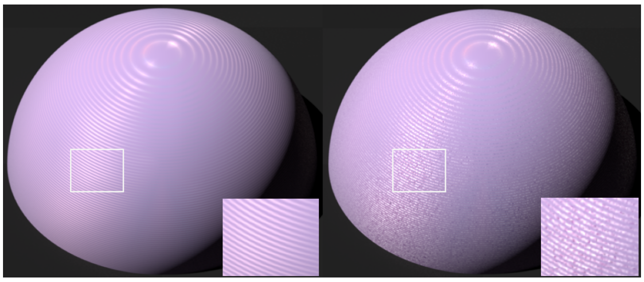

Figure 6: *Example of using predicted highlight variance to enhance the realism of 3D printed hemisphere renderings: a model (left) without computational prediction, and (right) with computational prediction of luminance variance.*

5. Conclusions

In two psychophysical studies involving 53 and 27 participants respectively, we assessed the perceived intensity and width of anisotropic highlights on 3D objects printed using 18 different filaments. The perceived values varied considerably across material filaments and the results of both experiments highly correlate. After testing several computational features, we determined that near-highlight contrast and the typical standard deviation of luminance values along the highlights are the most effective computational predictors of human judgments and can be used to improve predictive renderings of 3D printed surfaces. To stimulate further research, we have made the image and perceived data available on the project website.

Acknowledgments

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