Perceived Effects of Reflective Translucency in 3D Printing Filaments

Jiří Filip Martina Kolafová Radomír Vávra
The Czech Academy of Sciences
Institute of Information Theory and Automation
Prague, Czech Republic
filipj@utia.cas.cz

***Abstract*—3D printing becomes a standard for rapid prototyping and fabrication of customized parts. When it comes to appearance of the printed parts, it is highly affected by the printing filament type and its properties. This paper analyses reflective translucency of seventeen 3D prints and their original filaments. We performed a psychophysical study to obtain perceived translucency data, i.e. discriminability of background based on its reflection when passing through translucent material. These data are then compared with translucency measurements using a commercial device. Finally, we captured BRDF data of the filaments and used them to determine appropriate translucency measurement conditions.**

***Index Terms*—translucency, 3D print, filament, BRDF**

I. Introduction

When light encounters a material, it can interact with it in several different ways. These interactions depend on the wavelength, position, direction and polarization of the light and the structure and nature of the material. Resulting appearance is often a combination of reflection, absorption and transmission of incoming light. In the field of optics, translucency is the physical property allowing light to pass through the material while being scattered. In contrast to transparency common e.g for plate glass and clean water which transmit much of the incoming light and reflect little of it, the translucent materials manifest light scattering due to inner structure or presence of multiple materials with different indices of refraction. In contrast to opaque materials, the translucent ones reflect just a portion of incoming light while the remaining part is scattered and transmitted throughout the material's volume.

Various psychophysical experiments revealed [1], [2] that human perception of translucency, is not fundamentally based on underlying interactions of light with a given material, but is rather driven by simple low-level cues such as changes in contrast of either the object's surface itself or light from the background passing through the object. In fact, the perceptual notion of translucency encompasses multiple underlying aspects of physical light transport: lateral light transport within the object produces blurring of surface features and albedo color; vertical light transport allows us to see light passing through a highly translucent object from the opposite side.

This research has been supported by the Czech Science Foundation grant GA22-17529S.

Translucency is one of the major effects affecting appearance of 3D printing based on plastic filaments. In this paper we analyze perceived translucency and its relationship to data obtained from direct measurement of printed surface or original filaments. Instead of using active under-lighting of the material, we used a reflective translucency relying on visibility of reflected light from the background passing through the translucent material, specifically discriminability of transition of dark and light background below 3D printed tile. This approach allows a comparison of multiple translucency assessment approaches.

Main contributions of this paper:

- We performed a psychophysical study of perceived translucency on tiles printed by means of 17 different 3D print filaments and have shown that these results can be predicted computationally directly from image data.
- We applied a commercial color reading device to validate our results.
- Finally, we captured BRDF of individual 3D printing filaments and analyzed which illumination/view geometries provide the best fit to the perceived data.

II. Related Work

Appearance of 3D printing – 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 [3]. Clark et al. [4] 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. [5] 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.

Translucency perception – a recent review of the topic was presented by Gigilashvili et al. [6]. Fleming and Bűlthoff [1] found that many of the cues that were traditionally thought to be important for semi-transparent filters are not relevant for solid translucent objects. They discussed the role of highlights, color, object size, contrast, blur and lighting direction in the perception of translucency and argued that the physics of translucency are too complex for the visual system to estimate intrinsic physical parameters by inverse optics. Motoyoshi [2] demonstrated that manipulation of the contrast and blur of the non-specular image component dramatically alters the apparent translucency of an opaque object. The results support the notion that the spatial and contrast relationship between specular highlights and non-specular shading patterns is a robust cue for the perceived translucency and transparency of three-dimensional objects.

Translucency measurement – Weyrich et al. [7] measured translucency of the human face using a linear array of 28 fibers. One of the fibers acted as the illuminant, while the others acted as detectors measuring subsurface scattering fade-off. Finally, the BSSRDF model [8] was fitted to the measured data and used to support rendering. Yoshida et al. [9] developed a simple and effective method for measurement of translucency, applied to skin, with a handy spectral reflectometer using edge loss. Edge loss can be used to quantify the translucency index in terms of changes in reflectance under two types of measurement conditions based on pairing of an illumination area and a measurement area. Burton et al. [10] presented an efficient and scalable pipeline for fabricating full-colored objects with spatially-varying translucency from practical and accessible input data via multi-material 3D printing. They propose a framework for extending standard color management and profiling to combined color and translucency management using a gamut correspondence strategy. Authors present an efficient streaming method to compute voxel-level material arrangements, achieving both realistic reproduction of measured translucent materials involving multiple fully or partially transparent geometries. Urban et al. [11] propose a rigorous definition for RGBA translucency channel in a way suitable for use in graphical 3D printing. The definition is independent of the 3D printing hardware and software, and which links both optical material properties and perceptual uniformity for human observers. It is derived from the absorption and scattering coefficients of virtual homogenous reference materials with an isotropic phase function and it allows a simple translucency measurement and adjustment by commercial spectrophotometers used in graphic arts.

Several commercial devices and standards of transparent/translucent measurements exist, majority of them based on luminous transmittance or haze when passing through the tested sample in relation to reference specimen, e.g., ASTM D1003 [12], ASTM D1746-97 [13], ISO 13468 [14].

In this paper, we perceptually analyze reflective translucency of 3D printed objects and compare it with computational methods using images and BRDF data.

III. Test samples

For our experiments, we used 3D printing made from fifteen PLA (polyactic acid) and two PET (polyethylene terephthalate) (samples 13 and 17) filaments of width 1.7 mm shown in Fig. 1-left. Fig. 1-right show examples of object printed using these filaments.

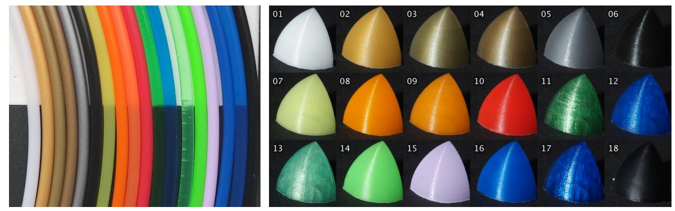

Fig. 1. Tested filaments and 3D prints obtained.

For purpose of out psychophysical analysis, seventeen flat tiles of size 20 x 20 mm were printed as shown in Fig. 2. Below the tiles a check board pattern was added so as under each tile were two white and two black squares forming a contrast background.

IV. Perceived translucency

In our online study observers have seen image of all samples as shown in Fig. 2 and evaluated translucency of individual printed tiles on an eleven-point Likert-like rating scale, where 0 corresponds to the lowest and 10 to the highest translucency. This range should represent only the span of materials within the study, i.e., the highest ratings should correspond to the material having the highest translucency from the study and not from the real world. We adapted this design as it is dominant in image and video experiments [15]. On the eighteenth place (bottom-right corner) no tile was placed and we the expected high translucency rating was used as catch trial-to check whether participant paid attention and understood the task correctly.

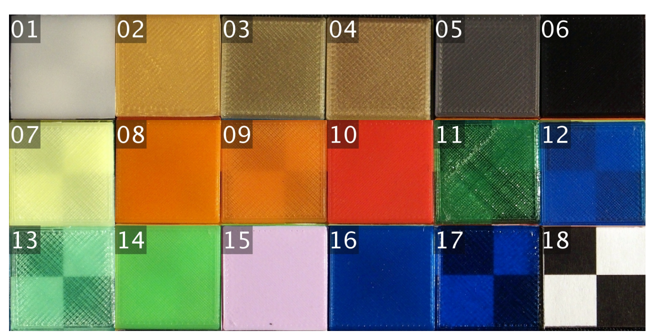

Fig. 2. 3D printed tiles of height 1mm used in the psychophysical study.

The participants rated reflective translucency for each material. They were asked: *Evaluate translucency of materials on a scale between 0 (minimum – corresponds to material No.6) and 10 (maximum – corresponds to material No.18).*

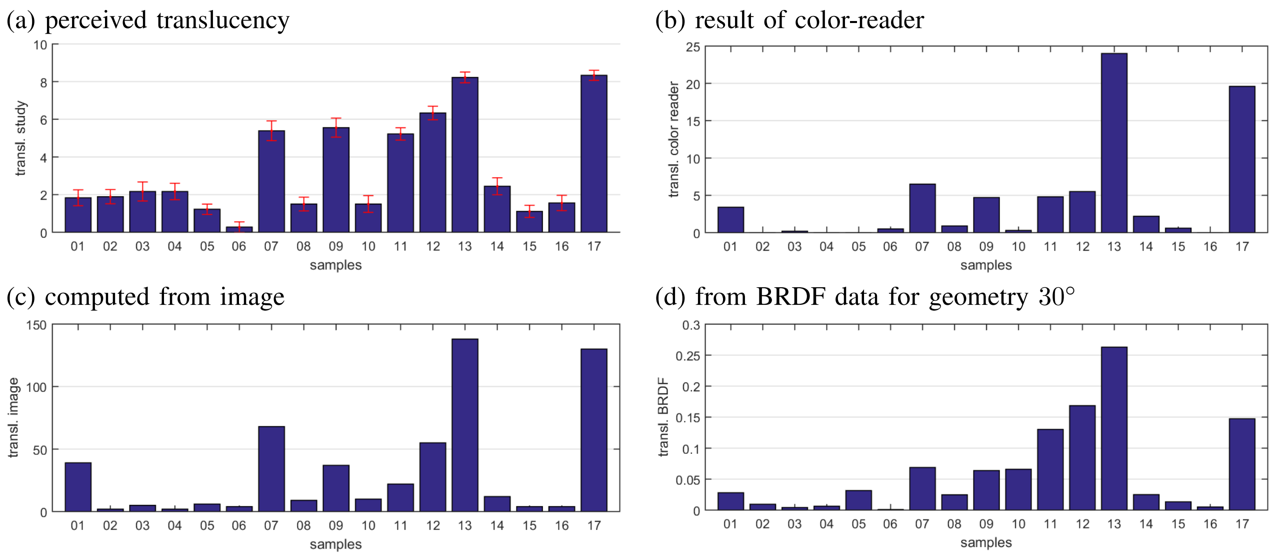

Fig. 3. Translucency rating obtained from (a) psychophysical study, (b) color reader, (c) image computational analysis and (d) BRDF measurement.

To make perceptual scaling tasks easier, each stimulus contained all evaluated samples. In total 20 participants participated in the study. As the study was running online, we have no information on participant age, but participants were naive with respect to the purpose of the experiment. All participants were instructed to perform the study only if they have normal or corrected-to-normal visual acuity.

Prior to data analysis, we checked on the presence of outliers and assessed agreement across participants. First, we performed outliers rejection by removing values differing from mean participant responses for more than 5 scale points. A total of 8 outliers were found representing 2.4% of 340 values recorded in the study. We did not observe any systematic behavior in assignment of outliers to materials.

Next, we checked participants' responses agreement using Krippensdorff alpha [16] – a statistical measure of the agreement generalizing several known statistics. The key requirement is agreement observed among independent observers. Output α_K = 1 represents unambiguous indicator of reliability, while 0 does not. The α_K value was 0.723, demonstrating a good agreement among the participants.

We also analyzed the significance of differences between samples' means using hypotheses testing of means of individual samples using repeated-measures ANOVA. The obtained zero p-value demonstrates a high significance.

To get insight into typical participants' responses, we computed the mean opinion score (MOS) obtained as average rating across all participants. This is standard methodology for a subjective quality assessment used particularly in the audio and video industries, and recommended by standard international organizations such as ITU [17] or ISO [15]. The mean opinion scores of the ratings ranging from 0 to 10 for tested materials are shown in Fig.3-a (row-wise ordering of tiles from the stimulus image). The error bars in the graph represent standard error values. The graph demonstrate that only six materials are perceived as significantly translucent, but responses indicated non-zero level of translucency for all materials. The standard errors are relatively low especially for highly translucent materials (13 and 17).

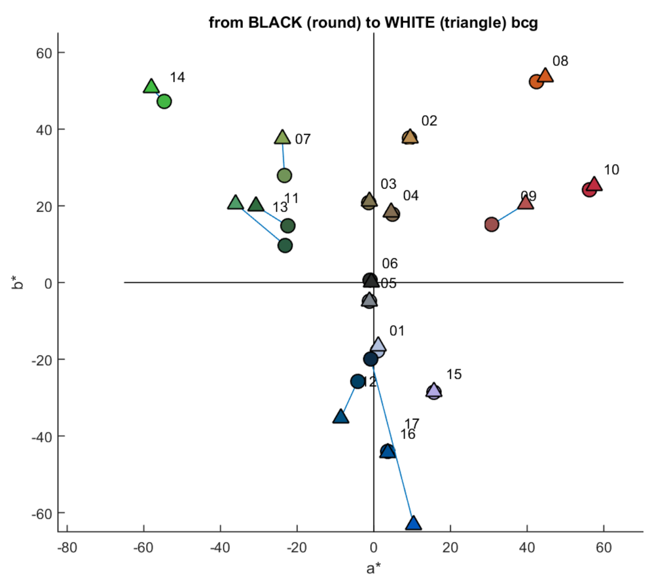

Fig. 4. Color shift of the tested samples due to translucency in CIE Lab color space.

V. Translucency model

To obtain a colorimetric reference for perceived reflective translucency, we used color-measurement device ColorReaderPRO by Datacolor [18]. It conveniently samples color of surface illuminated from $45°$ a returns its CIE Lab values. We used this device for sampling color of each printed tile in two locations one with white and one with black background.

The reflective translucency was obtained by subtracting values for black background from those for white background. The sum of difference across all Lab channels is shown in Fig. 3-b. The a-b color chart in Fig. 4 demonstrates importance of color for assessment of reflective translucency. It shows color-shift for the same tile but different background (triangles represent white and circles black background). We observe that sample backround does not affect luminance only, but also chromatic saturation. Therefore, in our further computational comparisons we always computed reflective translucency in all color channels. The Pearson correlation between results of the experiment and readings of the device converted to RGB was 0.90 (p-value 0.000001).

To computationally assess reflective translucency, we used image processing methods on the same image shown to participants in the experiment (see Fig. 2). From each tile image, two areas were selected, one corresponding to white I_W and one to black background I_B. The suggested model subtract median pixel values in both areas, and the differences are then summed across all the RGB color channels:

$$T = \sum_{c=1}^{3} (median(I_W) - median(I_B)) \tag{1}$$

Results of this computational model are shown in Fig. 3-c. The Pearson correlation between results of the experiment and computational prediction was 0.89 (p-value 0.000002). The correlation between computational prediction converted to CIE Lab and readings of the color measurement device across values from all color channels was 0.91 (p-value 0.000000).

Fig. 5. The tested filaments with two different backgrounds.

VI. TRANSLUCENCY IN BRDF DATA

A disadvantage of our computational model is requirement of printed object for assessment of reflective translucency. To allow the assessment directly from the printing filaments, we resorted to their BRDF measurement. A four-dimensional Bidirectional reflectance distribution function (BRDF) [19] describes the distribution of the radiance reflected to the specific viewing direction when illuminated from the other one. We captured BRDF of a tiny area of filament surface 0.02x0.02 mm with normal coincidental with sample ideal plane normal. We captured BRDF of individual filaments for both white and black background using SIGHTTEX Q material appearance capturing device. The device is based on a goniometric setup using five RGB camera and 28 non-polarized LED lights, both 300mm distant from the measured area of maximum size 40 x 40 mm. The measurement process took around 20 minutes and provided 3660 color HDR values in CIE XYZ colorspace. An example of filaments for both backgrounds are shown in Fig. 5.

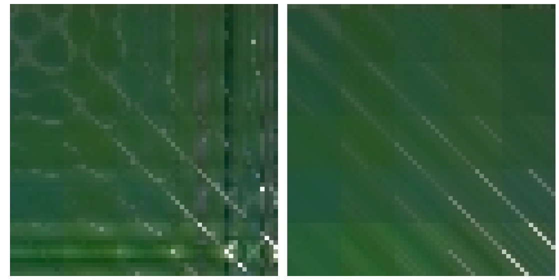

Fig. 6. An example of noisy measurement (left) and the result after enforcing isotropy and reciprocity (right).

The seventeen captured BRDFs for white and black background are shown Fig. 7-a,b. Note that each captured BRDF can be for the sake of visualization represented as an image of 61 x 60 directions, where rows corresponds to illumination directions and columns to viewing directions directions moving circularly from the pole of the hemisphere above the material to its bottom. Polar angles θ are sampled in $15°$ steps (for light $0°$, $15°$, $30°$, $45°$, $60°$, $75°$; for view $15°$, $30°$, $45°$, $60°$, $75°$). Within each polar angle 12 azimuthal angles are sampled. We compensated luminance attenuation due to illumited area foreshortening. However, the resulting data were noisy due to incorect alignment of the measured patch normal, surface imperfections, or due to the circular profile of the filament. Therefore, we enforced illumination/view directions reciprocity [19] and isotropy [20] to obtain smooth BRDFs as shown Fig. 6. Again the translucency is obtained by subtracting the BRDF with black background from the BRDF with white background and is shown in Fig. 7-c.

The BRDF measurement allow as to assess correlations for different subsets of illumination and viewing geometries to the visual data, i.e. even for those differing from illumination/viewing geometry approximately $0°/0°$ used in the experiment. This analysis can eventually provide guidance on geometry for translucency measurement. Tab. I lists Pearson's correlations between translucency obtained from BRDF at various polar angles θ and (a) results of psychophysical study and (b) readings of color measurement device. Note that while for (a) we used summed values across all RGB channels, for (b) we converted BRDF values to CIE Lab color-space and computed correlation on $3 \cdot 17$ long vectors. Tab. I shows averaged result across $12 \cdot 12 = 144$ illumination and view azimuths for individual polar angles. As expected, we observe lower correlation values with increasing polar angle, which is due to lateral translucency for illumination/view geometries non-observed in the psychophysical experiment. Also correlations with color reader device is lower, which might be due to its different asymmetrical illumination/view geometry $45°/0°$. However, this still requires complex measurement process, so we analyzed the correlations as functions of difference of illumination and view azimuthal angles. Results for this analysis are shown in Fig. 8. The red outline shows correlation

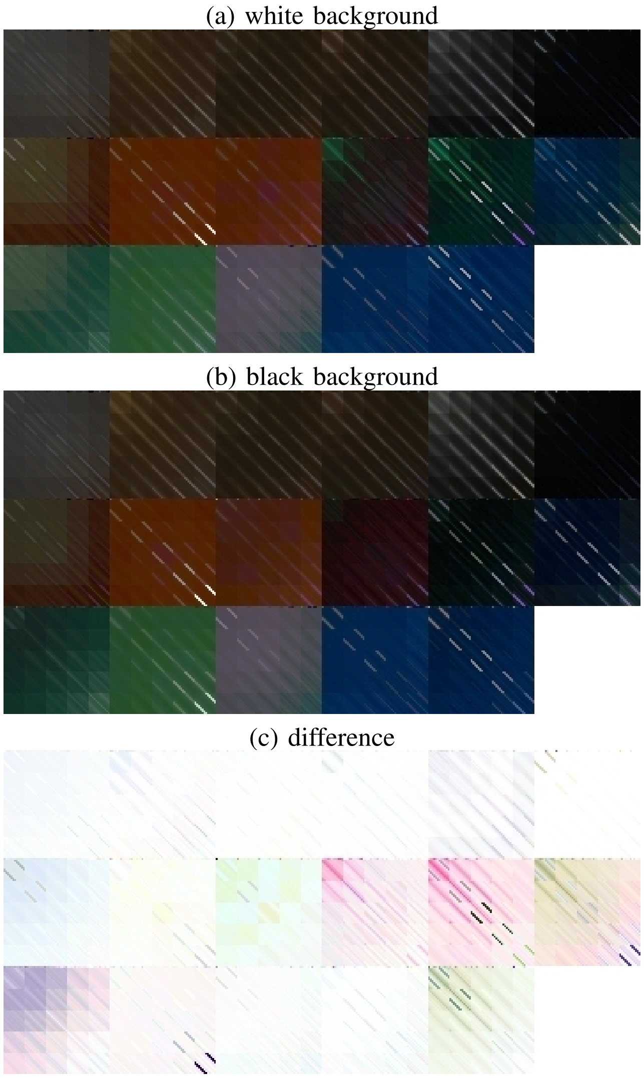

Fig. 7. Captured BRDF data of the tested filaments: (a) white background, (b) black background and (c) their difference.

TABLE I

A CORRELATION OF BRDF TRANSLUCENCY FOR DIFFERENT ILLUMINATION/VIEW GEOMETRIES WITH TRANSLUCENCY OBTAINED FROM THE EXPERIMENT AND FROM COLOR READING DEVICE.

polar angle	(a) perceived correl. coef.	(a) perceived p-value	(b) color reader correl. coef.	(b) color reader p-value
BRDF – all azimuthal combinations				
$\theta_i/\theta_v = 0°/15°$	0.79	0.00050	0.58	0.00000
$\theta_i/\theta_v = 15°/15°$	0.87	0.00003	0.64	0.00000
$\theta_i/\theta_v = 30°/30°$	**0.88**	0.00001	**0.69**	0.00000
$\theta_i/\theta_v = 45°/45°$	0.83	0.00026	0.53	0.00008
$\theta_i/\theta_v = 60°/60°$	0.65	0.01259	0.36	0.00958
$\theta_i/\theta_v = 75°/75°$	0.35	0.26854	0.12	0.40817

between the visual study and the BRDF and the blue outline between the BRDF and the ColorReaderPRO. Best correlation values are obtained for low polar angles, especially $15°$ and $30°$, regardless the difference of azimuthal angles. For higher polar angles the correlations attenuate at specular reflection with azimuthal angles difference $180°$ with peaks at orthogonal azimuthal angles (difference $90°$, $270°$). We suspect that this is due to the lateral translucency, which have properties different from those analyzed in the experiment. Therefore, the recommended setup for measurement of 3D printing filaments reflective translucency should used close to specular geometry at polar angles or below $30°$.

Additional advantage of BRDF measurement is, that it allows filament appearance visualization on any geometry, i.e., as it would be manufactured from filament skeleton painted inside by white or black solid coating. Such a rendering is shown in Fig. 9, where the top-left and bottom-right parts correspond to black and white background, respectively. For translucent materials we can observe clear diagonal seam across the image.

VII. Discussion

Our results show good agreement between results of psychophysical study, image-based model, color-reading device, and BRDF measurement. However, one can spot several major differences between results of the study and remaining approaches shown in Fig. 3.

First, participants marked some level of translucency even for the samples, that were completely opaque. We hypothesize that it relates to a guess rate, resulting from inherent structure of 3D printings (see Fig. 2), where participant focuses on variations in the opacity [2] or may imagine projection of checkerboard structure visible under clearly translucent neighboring samples. We should also accept possibility that the background checkerboard pattern may not be visible for subjects and the material can still be translucent due to lateral scattering of the incident illumination.

Second, in contrast to results of the study, all assessment methods tend to stretch translucency for materials 13 and 17. As those were PET filaments their appearance may differ from the other PLA filaments. Possibly our models miss an attenuation component for highly translucent materials, which might be a subject of our future work.

Our study was performed online presenting only low dynamic range image. It would be interesting to replicate experiment in a controlled study to see of results would differ when participants can observe samples in real.

One limitation of our BRDF measurement was small size and cylindrical shape of the filaments, which might affect light scattering in several ways. We assume that we suppressed these effects by enforcing isotropic behavior and by analysis of differential data only. The high correlation to color measurement device data suggest that our BRDF data are still sufficiently reliable representation of filament appearance.

VIII. Conclusions

This paper assesses reflective translucency of 3D printings and the original filaments. We started with translucency assessment of 3D printed tiles using a psychophysical experiment, which was used as baseline for comparison of other methods. Those were based on color measurement using commercial device and computational analysis of photograph. Finally, we

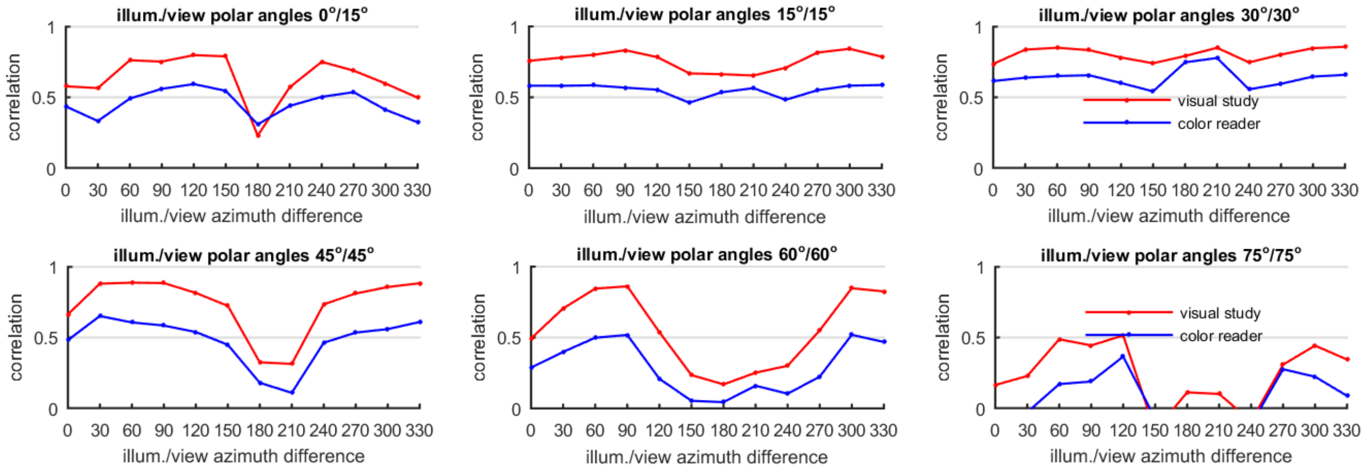

Fig. 8. Correlation with visual and color device data as a function of difference between illumination and view azimuths. Each graph shows different polar angles.

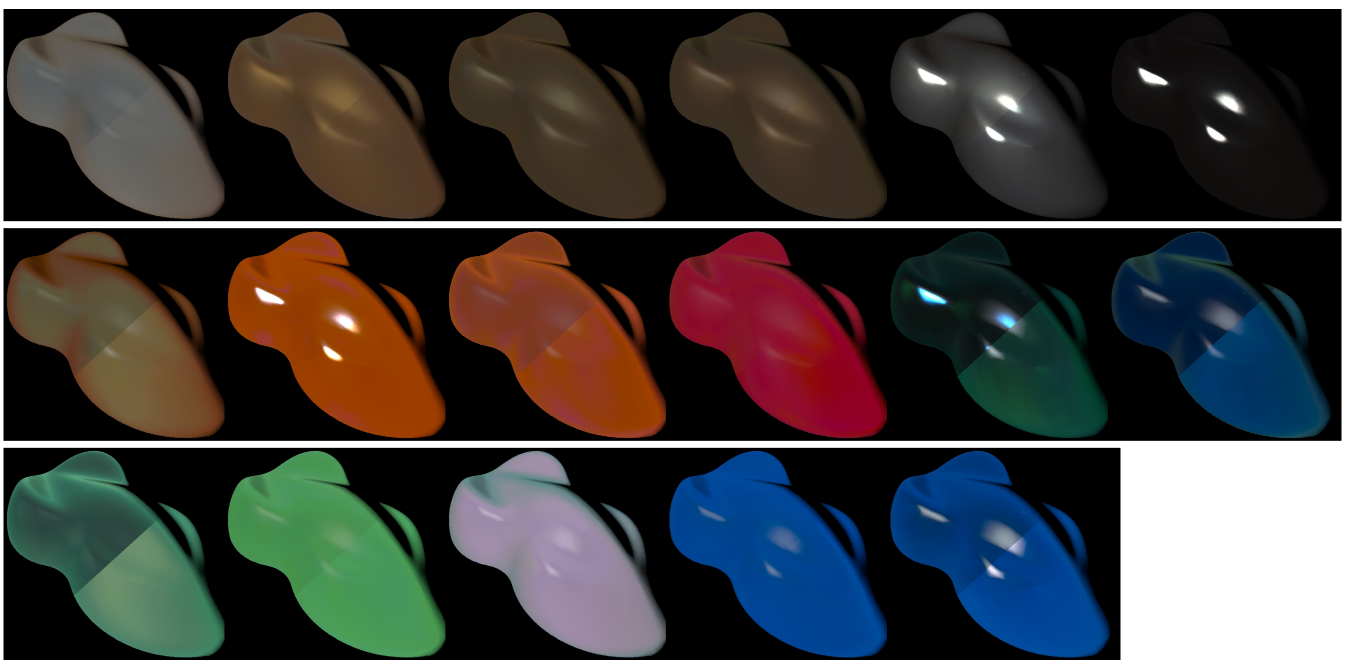

Fig. 9. Rendered images of the captured BRDF of individual filaments. It compares BRDFs captured for the black/white background of filament in top left/bottom right halves of the image.

captured BRDF of original filaments and analyzed different illumination/view geometries to find the best observation geometry for translucency. BRDF measurements show a high correlation to both visual data and colorimetric data. The paper demonstrates promising results for prediction of perceived reflective translucency of filaments. Our future work, will consist in research of translucency attenuation factor for highly translucent materials.

Acknowledgments

We would like to thank all volunteers taking part in the psychophysical experiments. Authors are grateful to Petr Vaníček from ÚTIA for 3D printing of the samples.

References

[1] R. W. Fleming and H. H. Bülthoff, "Low-level image cues in the perception of translucent materials," *ACM Transactions on Applied Perception (TAP)*, vol. 2, no. 3, pp. 346–382, 2005.

[2] I. Motoyoshi, "Highlight–shading relationship as a cue for the perception of translucent and transparent materials," *Journal of Vision*, vol. 10, no. 9, pp. 6–6, 2010.

[3] M. Taufik and P. Jain, "Role of build orientation in layered manufacturing: A review," *International Journal of Manufacturing Technology and Management*, vol. 27, pp. pp.47 – 73, 01 2014.

[4] A. T. Clark, J. F. Federici, and I. Gatley, "Effect of 3d printing parameters on the refractive index, attenuation coefficient, and birefringence of plastics in terahertz range," *Advances in Materials Science and Engineering*, vol. 2021, no. ID8276378, 2021.

[5] J. Filip, M. Kolafová, and R. Vavra, "A psychophysical analysis of fabricated anisotropic appearance," in *Pacific Graphics Short Papers*. The Eurographics Association, 2019.

[6] D. Gigilashvili, J.-B. Thomas, J. Y. Hardeberg, and M. Pedersen, "Translucency perception: A review," *Journal of Vision*, vol. 21, no. 8, pp. 4–4, 2021.
[7] T. Weyrich, W. Matusik, H. Pfister, B. Bickel, C. Donner, C. Tu, J. McAndless, J. Lee, A. Ngan, H. W. Jensen, and M. Gross, "Analysis of human faces using a measurement-based skin reflectance model," in *ACM SIGGRAPH 2006 Papers*, ser. SIGGRAPH '06. New York, NY, USA: ACM, 2006, pp. 1013–1024.
[8] H. W. Jensen, S. R. Marschner, M. Levoy, and P. Hanrahan, "A practical model for subsurface light transport," in *Proceedings of the 28th annual conference on Computer graphics and interactive techniques*, ser. SIGGRAPH '01. New York, NY, USA: ACM, 2001, pp. 511–518.
[9] K. Yoshida, N. Komeda, N. Ojima, and K. Iwata, "Simple and effective method for measuring translucency using edge loss: optimization of measurement conditions and applications for skin," *Journal of Biomedical Optics*, vol. 16, no. 11, p. 117003, 2011.
[10] A. Brunton, C. A. Arikan, T. M. Tanksale, and P. Urban, "3d printing spatially varying color and translucency," *ACM Transactions on Graphics (TOG)*, vol. 37, no. 4, pp. 1–13, 2018.
[11] P. Urban, T. M. Tanksale, A. Brunton, B. M. Vu, and S. Nakauchi, "Redefining a in rgba: Towards a standard for graphical 3d printing," *ACM Transactions on Graphics (TOG)*, vol. 38, no. 3, pp. 1–14, 2019.
[12] ASTM, "D1003: Standard test method for haze and luminous transmittance of transparent plastics," *West Conshohocken PA: ASTM International*, 2021.
[13] ——, "D1746-97: Standard test method for transparency of plastic sheeting," *West Conshohocken PA: ASTM International*, 2002.
[14] ISO, "13468-1:2019: Plastics – determination of the total luminous transmittance of transparent materials," 2021.
[15] B. Keelan, "ISO 20462: A psychophysical image quality measurement standard," in *Proceedings of the SPIE, vol. 5294*, ser. SPIE 2003, 2003, pp. 181–189.
[16] A. F. Hayes and K. Krippendorff, "Answering the call for a standard reliability measure for coding data," *Communication methods and measures*, vol. 1, no. 1, pp. 77–89, 2007.
[17] ITU, "ITU-R.REC.P.910. subjective audivisual quality assessment methods for multimedia applications," International Telecommunication Union, Tech. Rep., 2008.
[18] "Color Reader PRO, datacolor, https://www.datacolor.com/colorreader/, accessed 18/08/2022."
[19] F. Nicodemus, J. Richmond, J. Hsia, I. Ginsburg, and T. Limperis, "Geometrical considerations and nomenclature for reflectance," *NBS Monograph 160*, pp. 1–52, 1977.
[20] J. Filip, "Analyzing and predicting anisotropic effects of BRDFs," in *In proceedings of ACM SIGGRAPH Symposium on Applied Perception (SAP)*, September 2015.