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Optical properties and appearance of fused deposition modelling filaments

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Short abstract

The appearance of 3D-printed objects is affected by numerous parameters. Specifically, the colour of each point on the surface is affected not only by the applied material, but also by the neighbouring segments as well as by the structure underneath it. Translucency of the 3D printing inks is the key property needed for reproduction of surfaces resembling natural materials. However, the prediction of colour appearance of translucent materials within the print is a complex task that is of great interest. In this work, a method is proposed for studying the appearance of translucent 3D materials in terms of the surface colour. It is shown how the thickness of the printed flat samples as well as the background underneath affect the colour. By studying diffuse reflectance and transmittance of layers of different thicknesses, apparent, spectral optical properties were obtained, i.e., extinction and scattering coefficients, in the case of commercially available polylactic acid (PLA) filaments for Fused Deposition Modelling (FDM) printers. The coefficients were obtained by fitting a simplistic model to the measured diffuse reflectance as a function of layer thickness. The results were verified by reconstructing reflected spectra with the obtained parameters and comparing the estimated colour to spectrophotometer measurements. The resulting colour differences in terms of the CIEDE2000 standard are all below 2.

Keywords: 3D printing, appearance, optical properties, PLA filaments, translucency

1. Introduction and background

Unlike in traditional 2D printing, it is possible to apply materials in layered structures in Fused Deposition Modelling (FDM) 3D printing. The technique is based on applying melted filament in a layer-by-layer manner. Although not originally used for the purposes of appearance reproduction, this possibility is being actively explored (Hergel and Lefebvre, 2014; Reiner, et al., 2014). Current FDM printers offer the possibility of combining several filaments within one print (Espalin, et al., 2014; Khondoker, Asad and Sameoto, 2018). Together with slicing and instrument path strategies (Kuipers, et al., 2018; Song, et al., 2019), it is possible to recreate different colour shades within the built surface. There is a rich variety of commercially available filaments for FDM printing of different colours and special effects (glossy, semi-transparent, etc). An important visual trait of any 3D material is its translucency, that is, its ability to let light penetrate the material and re-emerge from the surface after multiple subsurface scattering events. Typically, it is required to apply > 1 mm thick layers until the colour of the applied material saturates and the impression of the layer is not affected by the layers underneath. At the same time, available fused deposition modelling 3D printers are able to apply filament in layers as thin as 50 μm. A combination of layers of two different materials therefore has a potential to create a number of colours on the outer surface, depending on the layer order and their thicknesses (Babaei, et al., 2017). If intrinsic optical properties are known, it is possible to predict the diffuse reflectance of a print using an existing solution of the radiative transfer equation, like the Kubelka-Munk formulas (Kubelka and Munk, 1931; Kubelka, 1948) or multiflux models (Simonot, et al., 2016). It is also possible to use known optical properties for simulating/visualising the appearance of a surface using physically based rendering techniques (Pharr, Jakob and Humphreys, 2017).

This is called soft proofing. The main optical properties that affect the colour appearance of a print are extinction and scattering properties. 3D printing can directly provide samples for the purpose of estimating the optical properties, as the dimensions of the produced samples can be precisely controlled. The effect of the layer thicknesses on the colour appearance by preparing a set of straight layers and collecting spectral reflectance and transmittance values is being studied. These values are represented either by spectral reflectivity, or by CIELAB values. Reflectivity values of defined 3D printed samples can be sufficient for characterizing a printer with data driven approaches described by Chen and Urban (2021). However, the ability to reveal and use material parameters are necessary for the physical models. After collecting reflectance data of the samples of different thicknesses, the effect of material thickness for each wavelength is analysed. Spectral diffuse reflection that contributes to the visual perception of the surface can be measured with a spectrophotometer. This device is commonly used for 2D prints, where the paper with ink absorbed in it is being characterised. From the 3D printing perspective, it is not sufficient to only consider absorption of the ink, because of the multiple interactions within the volume and contribution of the environment to the final appearance. It is important to distinguish between the absorption and scattering by the used materials. The target of this work is to predict colour appearance of the printed layers of filament. This report shows how a prediction can be made and how the necessary optical properties can be obtained from collecting sets of spectral power distribution (SPD) measurements of differently thick printed layers.

2. Materials and methods

In this work, commercially available FDM filament Neon Pink PLA from Prima Creator was chosen. The samples were prepared with a Flashforge Creator 3 3D printer. For the SPD measurement, a Barbieri SPF LFP 2 series spectrophotometer was used. The parameters were set as follows: D50 illuminant, 8 mm aperture, 45°/0° light/view configuration for the reflectance measurement. Transmittance measurements were performed under D50 illuminant and 8 mm aperture. The spectral range of the measurement is 380-780 nm. For accurate spectrophotometer measurements, the sample thickness should not exceed 2 mm. As samples, 2 cm × 2 cm squares with varying thickness between 0.1 mm and 1 mm were printed. In order to 3D print the samples, 3D models were created and sliced, so that the instrument path could be generated. A sample can be built using different thickness of each applied filament layer, different pattern with which internal volume will be printed, and the density of infill. In our experiment, the slicing parameters were set as follows: first layer thickness 0.1 mm, each next layer 0.05 mm, volume fill pattern was chosen as lines with direction rotating by 90° at each layer, 100 % infill density. Figure 1 demonstrates appearance of the printed samples placed on the white paper.

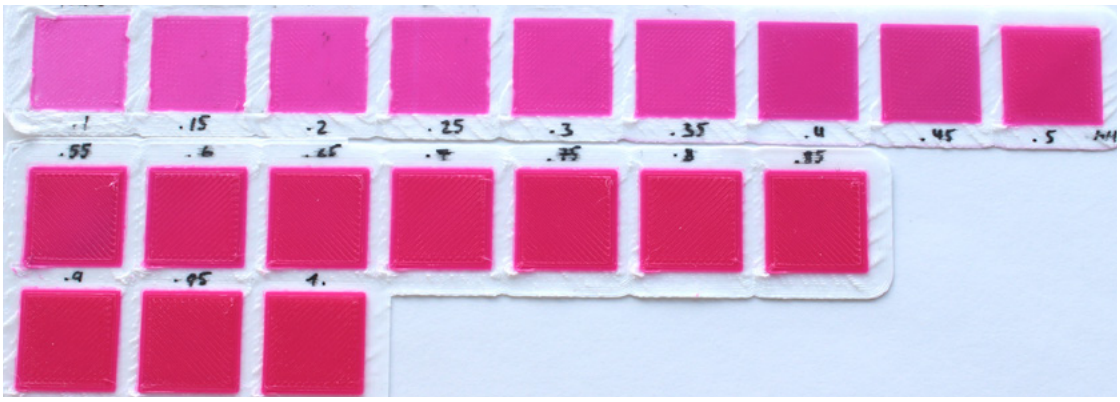

Figure 1: Printed samples of Neon Pink PLA of thicknesses 0.1 mm to 1 mm photographed on a white background; because of the material translucency, the background is affecting the surface colour, especially for the thin samples

After printing the samples, four sets of spectrophotometer measurements for each sample were performed. Reflection measurements were repeated for three different backgrounds below the sample: white paper, black paper and a mirror. The fourth set was transmission measurement. Each individual measurement was repeated five times each with a slightly different position and orientation of the sample, and the mean value was taken. This approach accounts for the imperfections on the surface caused by the printing process and compensates for the regular line patterns.

A practical model for predicting the variation in appearance for different backgrounds and different layer thicknesses is needed. To this end, a simple 1D light transport model was employed: light propagates upwards or downwards in the medium. The direction of the incident light is thus neglected, except for the fact that the reflectance of the background material is affected by the direction of incidence. If measured alone, mirror background results in almost perfect black SPD, as all incident light at a 45° angle of incidence will be reflected away, and nothing will be measured under 0°. However, when a layer of scattering material is included, part of the incident light will be scattered so that some of the light will be reflected to the normal direction. The amount of redirected light can be related to the thickness and scattering properties of the material. SPD of each sample was measured and then modelled with the following function accounting for extinction and diffuse reflection by the material:

$$R_\mathrm{m} = \int_0^D Re^{-2\alpha x}dx + R_\mathrm{b}e^{-2\alpha D} \qquad [1]$$

where R_m is the measured reflectivity, the apparent extinction coefficient of the material and D is the sample thickness. The exponential term represents extinction according to Bouguer's exponential attenuation law (Perrin, 1948), and R is the reduced coefficient representing diffuse scattering of the material. In our assumptions, R_b represents effective background reflectivity due to the bare background reflectance and the scattering in the material.

Measured transmittance data T_m were also modelled using the exponential attenuation law:

$$T_\mathrm{m} = e^{-\alpha D} \qquad [2]$$

All four sets of measured reflected and transmitted spectral distributions were modelled simultaneously with Equations [1] and [2]. The spectral dependency is described by spline functions. Parameter R and shared parameter α were fitted for each wavelength. For each background, an individual parameter R_b was fitted. After the material parameters were obtained, they were used as a benchmark to reconstruct spectral density by applying material parameters in Equation [1]. Obtained SPDs were used to compute CIELAB values which were compared to the originally measured ones in terms of CIEDE2000 standard.

3. Results and discussion

The spectral power distribution values collected during the measurements for each sample result in the colour perceived by the observer. The samples with thickness up to 1 mm are not opaque. Thus, the background below the sample affects the colour on the surface. This results in lighter shades in case of the white background and darker if the black background is used. Figure 2 demonstrates CIE *xy* chromaticity diagrams of samples with different thicknesses on different backgrounds. As the thickness increases, the background will contribute less to the top surface appearance. This can also be seen from Figure 3, where the evolution of the reflectance values with the sample thickness is shown for one chosen wavelength of the SPD. For three different backgrounds, a tendency of the colour of increasing thickness of the samples to saturate toward the common point can be seen.

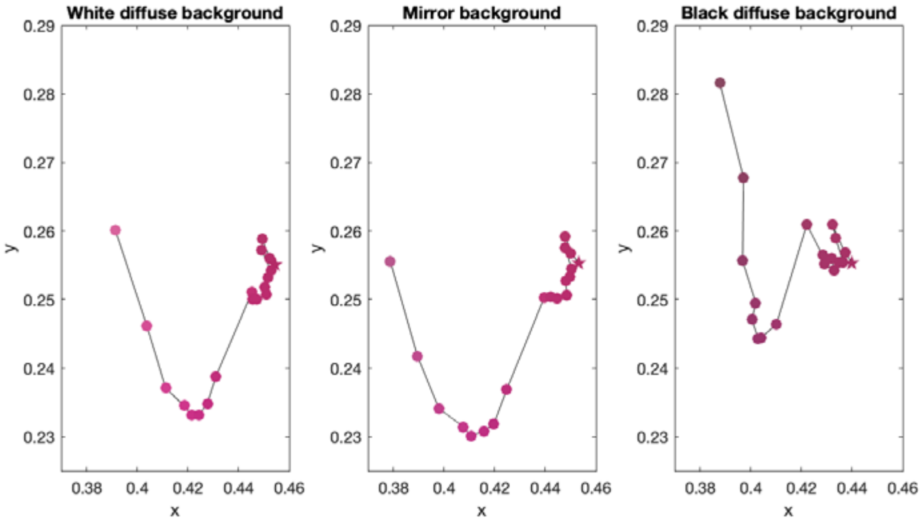

Figure 2: CIE xy chromaticity diagrams representing measured colour of the samples of Neon Pink filament of thickness 0.1 mm to 1 mm in steps of 0.05 mm; coordinates correspond to the CIE x and y values, the colour of the points represents RGB values calculated from the measured diffuse reflectance values, data for the 1 mm thick sample are marked with a star

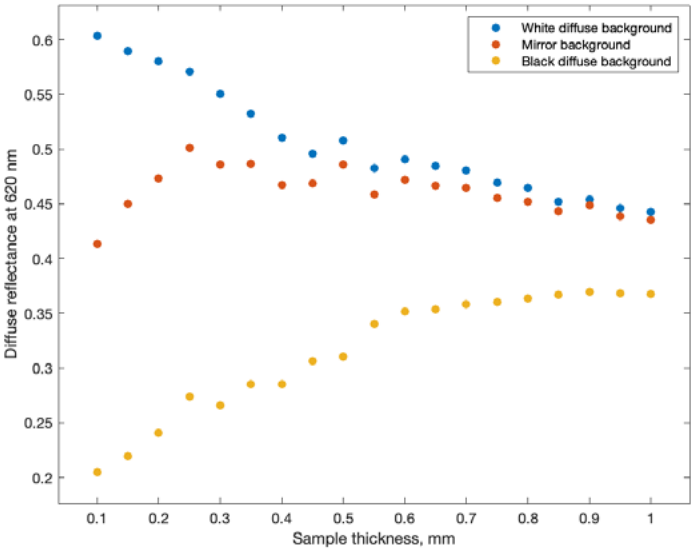

Figure 3: Diffuse reflectance at 620 nm with increasing sample thickness for all three backgrounds; as the thickness of the sample increases, the contribution of the background becomes less evident, and the values slowly approach a common saturation point

In Figure 4, the apparent extinction coefficient α and the apparent scattering coefficient R resulting from our fits is plotted. Notably, the spectral line shape of the fitted scattering coefficient resembles the (rescaled) derivative of the extinction coefficient with respect to photon frequency. This indicates that the approach is consistent with expectations of physically meaningful dispersion, according to the Kramers-Kronig relations (Jackson, 1975). The apparent scattering coefficient is mostly a result of polydispersity of the real part of the refractive index, while the apparent extinction coefficient is a result of both material extinction (the imaginary part of the refractive index) and scattering.

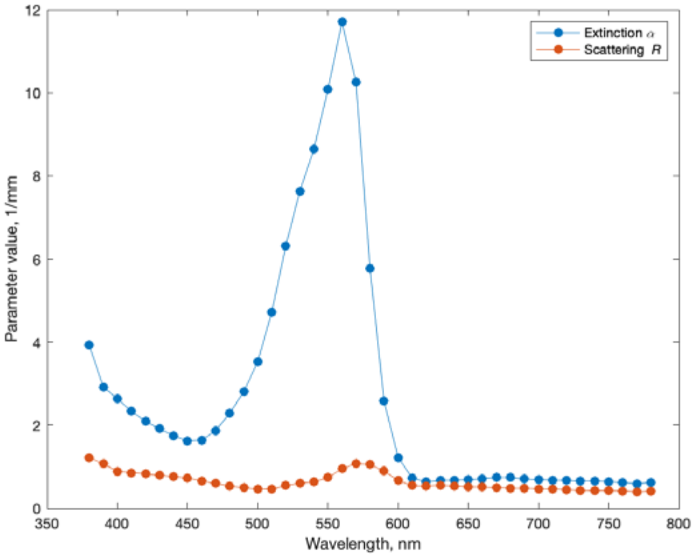

Figure 4: Effective extinction α and reduced scattering coefficient R obtained from the fit

The obtained extinction and scattering coefficients together with fitted effective surface response R_b were plugged into Equation [1]. By doing this, the diffuse reflectance values were reconstructed. Figure 5 demonstrates comparison between originally measured and reconstructed reflectance for the samples of the thickness of 0.1 mm, 0.5 mm and 1 mm on white diffuse background.

In order to quantitatively assess the difference, CIELAB values were calculated using the reconstructed reflectance spectra and assuming a D50 light source. Those values were compared to the originally obtained CIELAB values from the measurements in terms of CIEDE2000 standard. The results of comparison for all samples and each background are shown in Figure 6. As can be seen, the colour difference values are stochastically distributed across the mean value. No tendency with sample thickness can be observed, which indicates absence of a strong systematic error in our simplistic 1D radiative transfer model approach. There are discrepancies in the red spectral range, where the material is weakly absorbing. This can indicate insufficient consideration of the spatial distribution of the scattered light. The obtained values for colour difference below 2 show that the method is well suited for the main purpose, i.e., colour prediction.

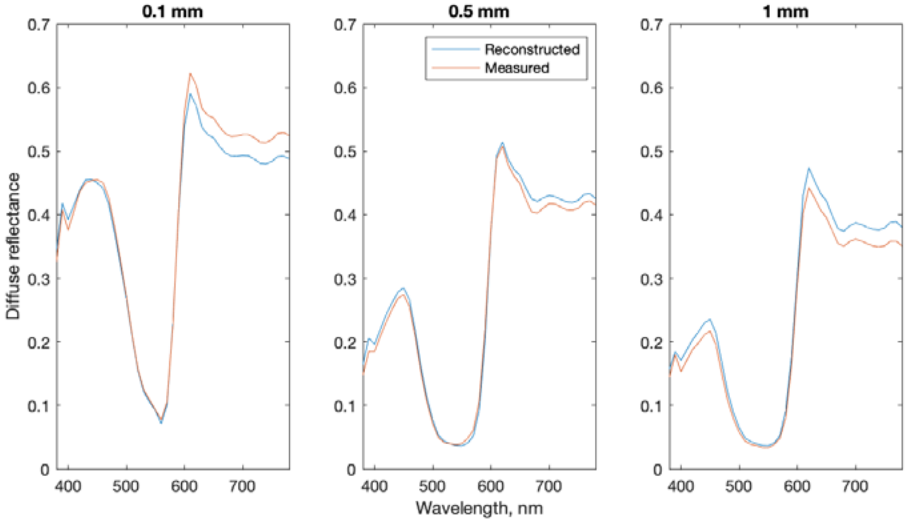

Figure 5: Comparison of the reconstructed diffuse reflectivity and the originally measured one for samples of the thickness of 0.1 mm, 0.5 mm and 1 mm on white diffuse background

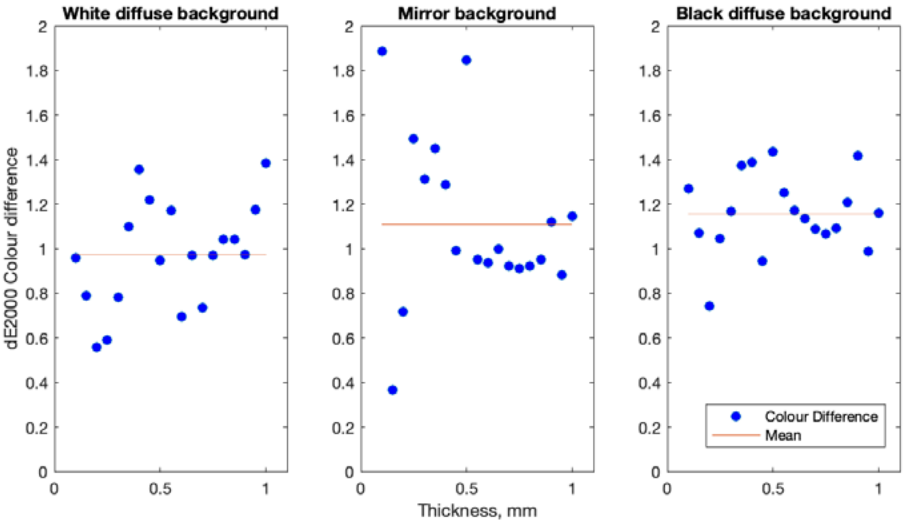

Figure 6: Colour difference between measured and reconstructed reflectivity values for all three backgrounds and each sample

4. Conclusions

In this work, a study of colour appearance of PLA filament with increasing thickness was made. A set of transmission and reflection measurements on three different backgrounds was used to obtain apparent extinction and scattering coefficients. The resulting coefficients are consistent with the expectations, i.e., the largest extinction of the pink material occurs in the green. Using a simplistic 1D radiative transfer model, it was possible to predict the spectral diffuse reflectance of layered PLA filaments and their combinations. This approach enables prediction based on physical assumptions as opposed to an approach based purely on machine learning. In this work, the samples were printed on an FDM 3D printer. This manufacturing method imprints certain surface artifacts caused by the instrument path. Therefore, the material parameters revealed during the experiment have apparent character. Further studies can be carried out in order to determine the effect of the volume and surface structure on the scattering and absorption properties of the samples. The method is not restricted to the PLA FDM samples, and it is possible to apply it on arbitrary materials produced by depositing layers of known thickness acceptable by the spectrophotometer. As a step of further work, one could assume that the scattering properties obtained in this work are valid in all directions. Our work is thus useful for studying the crosstalk between the neighbouring points of a print.

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