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The Effect of Surface Texture on Color Appearance of 3D Printed Objects

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Abstract

3D printing has become an increasingly popular and affordable technology in recent years due to rapid technological advances. One such advancement is the ability to print a single object with multiple colors. Traditional printers work on the assumption that the surface they are printing to is flat, which further assumes that surface geometry has a negligible effect on appearance. The International Color Consortium (ICC) builds profiles allowing for color communication amongst devices, including traditional 2D printers. The ICC does not currently have practices in place to build profiles for color 3D printers, due in part to several unknown parameters affecting the appearance of 3D printed objects. One such unknown is surface texture. To test the effect of surface texture on the color appearance of 3D printed objects, 3D models were built digitally with goniochromatic effects in mind and then printed using a color 3D printer. Spectral radiance and BRDF measurements of the 3D printed samples were taken to test for changes in appearance. It was found that surface texture does have a measurable effect on the color appearance of 3D printed objects, which is an important first step in creating a characterization space for color 3D printers.

Introduction

A study conducted by Domingue et al. attempted to fabricate female emerald ash borers, beetles with an iridescent appearance, with enough accuracy that male beetles would be attracted to them.[1] Decoy beetles were produced using several techniques, one of which was 3D printing. The printed decoys were painted with metallic paint in an attempt to mimic the iridescent appearance of living beetles, while the other decoys were colored using different methods.

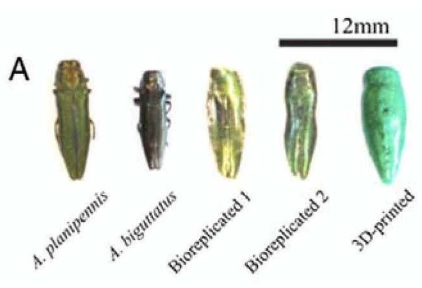

***Figure 1**: The two beetles shown on the left are images of actual beetles. The three to the right are decoys.[1]*

Of all the beetle decoys used in this study the 3D printed decoy produced the weakest results. The primary issue with the 3D printed decoy was that it was highly reflective due to the metallic paint, but it did not produce a strong goniochromatic effect. This study served as the inspiration for the current project, which aims to create color 3D printed objects with measurable and observable goniochromatic effects.

What would later become known as 3D printing began as a technology called stereolithography, first patented by Charles Hull in 1986.[2] The original idea was to add materials layer by layer until the desired shape was achieved. Technological advances have caused this concept to gain traction in recent years and develop into 3D printing's current state. As this technology continues to develop and become increasingly affordable, the range of available materials and applications is expected to grow. Along with new applications will come new challenges, one of which is how to print individual objects with multiple colors. Traditionally, most 3D printers have only been capable of printing one color at a time. That is changing as the number and quality of 3D printers able to print multiple colors in a single assembly is increasing.

The ICC is an organization that sets standards with regards to color communications between devices. ICC profiles are used to translate color data created on one device to another device's native color space. For example, an image captured by a cell phone's RGB camera can be sent to a printer, which prints using CMYK primaries. Without some type of color management, such as ICC profiles defined for both the camera and the printer, the printed image would be unlikely to accurately reproduce colors found in the camera's image.

With the introduction of a new ICC specification, iccMAX, parameters affected by surface geometry, such as bidirectional reflectance distribution function (BRDF), can be used to build ICC profiles.[3] Previous work funded by the ICC was similar to this work in that it took BRDF measurements of real objects, though the aim of that study was to optimize BRDF measurement and color appearance for simulation using iccMAX and the Blinn-Phong and Cook-Torrance models.[4] Other work has also been done to optimize uniformity of surface appearance for color 3D printed objects, though that study did not take the effect of non-uniformity along surfaces into account.[5] The current project aims to explore parameters known to affect appearance, primarily goniochromatic properties, to determine which are necessary to define an appearance gamut for color 3D printed objects. This would be a first step towards creating profiles for 3D printers within the iccMAX architecture. This is important since ICC profiles for traditional 2D printing make the assumption that surfaces are flat and geometrically uniform.

The challenge in reproducing goniochromatic effects, such as the iridescent appearance of beetles, using modern 3D printers is that the minimum size printers can achieve is restricted by the minimum size of materials used. The printer used in this study, a Stratasys® J750, can print details as small as 0.014 mm. While printing a 3D object on a micro-scale in multiple specified colors is impressive, iridescence is the result of constructive and destructive interference of light, which is the result of physical nano-scale surface geometries. While interference cannot be truly replicated by present day 3D printers, comparable goniochromatic effects may still be mimicked by varying the surface geometry of objects printed in multiple colors.

Methods

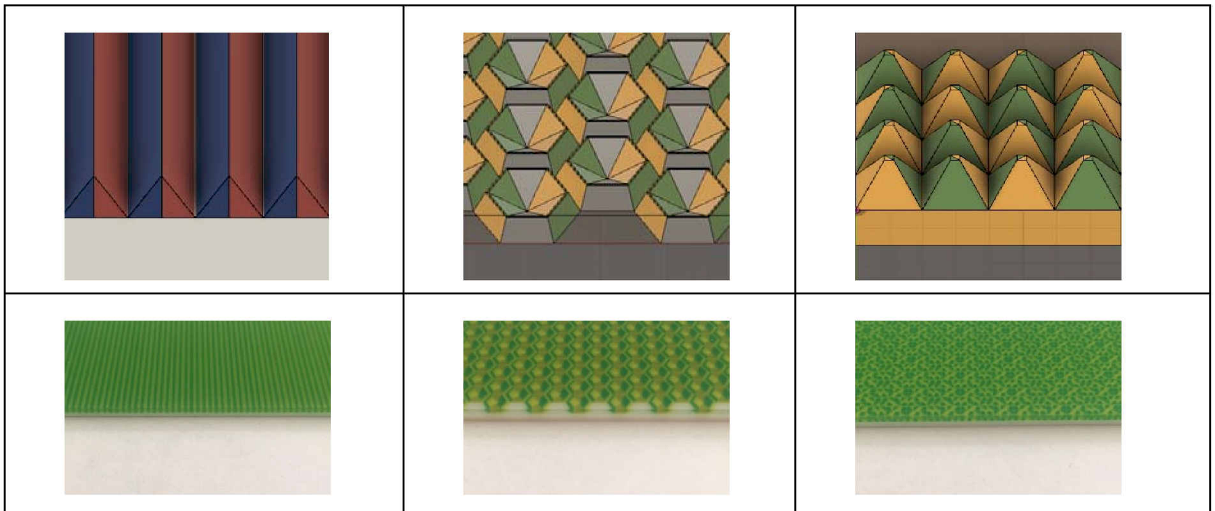

Figure 2: Top row: Objects modeled in Autodesk® Fusion 360. Bottom row: Same objects printed using a Stratasys® J750 3D printer. Modeled samples do not match the color of printed samples as the Autodesk® Fusion 360 color palette was limited. Samples, starting from the left, are referred to as 'tent', 'honeycomb', and 'pyramid' after the shape of the geometries used.

In order to study goniochromatic effects, 3D printed objects with flat surfaces and varying sub-surface geometries were produced. 3D renderings were first created using Autodesk® Fusion 360 software. The renderings each had different geometries, which were then covered by several layers of transparent material. This resulted in samples with a flat surface but non-uniform 3D geometries.

The renderings, shown in the top row of Figure 2, were sent to Stratasys® Direct Manufacturing where they were printed using a Stratasys® J750 3D printer. So far, three such models have been designed and printed.

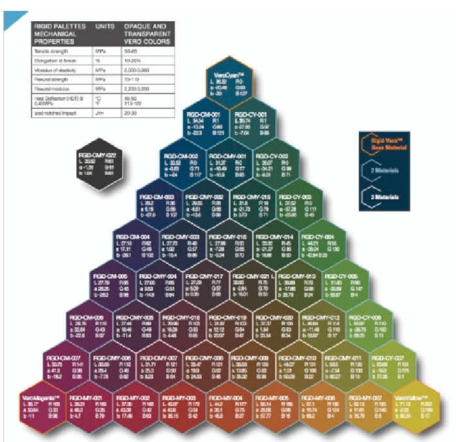

Figure 3: Sample page from the Polyjet Color Guide.[6]

The Stratasys® J750 can print a relatively wide range of colors. Most 3D printers can only print one color at a time but the Stratasys® J750 can print multiple colors on a single part using CMYKW primaries, which is similar to traditional 2D printers only with a white included. These are detailed in the Polyjet Color Materials guide, which was provided by Stratasys®. The colors selected were inspired by the CIELAB values of emerald ash borers, which were measured for a previous class project.

Figure 4: Micrograph image of an emerald ash borer.

Table 1: Example CIELAB values from measurements of an emerald ash borer.

	Elytra	Eye	Side	Belly
L*	22.83	40.62	21.46	26.19
a*	-9.08	-22.13	-12.31	-4.68
b*	10.30	22.39	11.47	8.30

Table 2: CIELAB values of materials used in 3D prints.

	RGD-CY-003	VeroYellow	RGD-CMY-012
L*	37.52	71.12	46.64
a*	-37.28	-2.03	-11.48
b*	25.95	90.24	50.87

The measurements taken from the beetles themselves were relatively low chroma. Visual inspection of the beetle and the desire for a measurable goniochromatic effect were also taken into account when deciding on the Polyjet colors to use. In the end green and yellow colors were chosen as they most closely matched the beetle's color appearance, which can be seen in Figures 1 and 4. While the beetle in Figure 4 appears more dark blue than light green and yellow, this was taken with a micro-lens and did not closely match with a naked-eye view. Unfortunately no further information was provided by Stratasys® regarding the methods used to acquire the Polyjet CIELAB values. This is a potential limitation, especially given the apparent translucency of the printed samples.

Note that a third color, RGD-CMY-012, was used only for the 'Honeycomb' sample as a transitionary color. The CIEDE2000 color difference was calculated for RGD-CY-003 and VeroYellow. The difference between these two colors and several others from the Polyjet Color Guide was then calculated in order to choose a third color that would lie closest to the perceptual center.

Radiance measurements were taken using a PR-655 SpectraScan spectroradiometer. The samples were placed on a stationary target while the PR-655 was mounted onto a rotating arm in front of them. The light source was placed behind and above the PR-655 and faced directly towards the samples at an angle of approximately 45°. The light source remained stationary during all measurements so that only the angle of observation was varied. Measurements were taken at every 5° up to 80° outward on either side of the sample's surface normal.

Once radiance measurements were taken from the samples, a halon sample was also measured to act as a perfect reflecting diffuser (PRD). A PRD is a Lambertian surface, which means incident light is reflected diffusely in all directions.[7] The sample radiance was divided by the PRD radiance to calculate reflectance factor. CIEXYZ tristimulus values were then calculated using D65 as the illuminant and the 1931 2° standard observer's color matching functions. Illuminant D65 was selected with the emerald ash borers in mind since they would primarily be viewed in daylight. CIELAB values could then be calculated using a D65 white point, along with CIEDE2000 color differences.

BRDF measurements were taken using a Murakami goniospectrophotometer. BRDF measurements are important for characterizing object appearance due to the effect non-uniform 3D geometry can have on appearance. This device allows for precise, automated measurements while varying both angle of incidence and angle of observation. The angle of incidence ranged from 0 to 75° in steps of 15°, while the angle of observation ranged from 0 to 75° in steps of 5°, or 2° if close to the specular angle. The reflectance measurements taken with the goniospectrophotometer were used to calculate CIEXYZ tristimulus values and CIELAB values as described above.

Each of the three samples printed appeared to be somewhat translucent. While the transmittance of the samples was not measured directly, the samples were measured with both a black and white backing to see what effect this may have on color measurements.

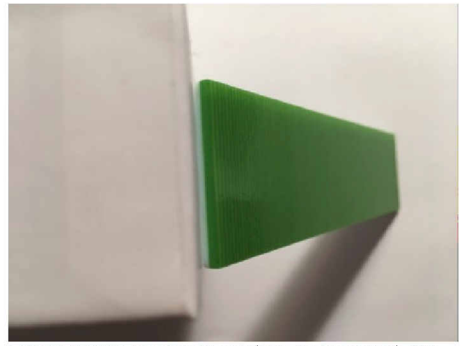

***Figure 5**: Tent sample viewed from measured left side.*

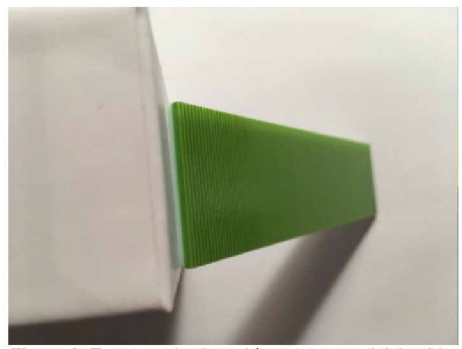

***Figure 6**: Tent sample viewed from measured right side.*

Figures 5 and 6 show the tent sample from both sides. In these images one side appears greener and the other yellower. While this is apparent from the extremes, gradual changes in color appearance should occur as the objects are rotated from the center.

Gonio-Arm Measurements

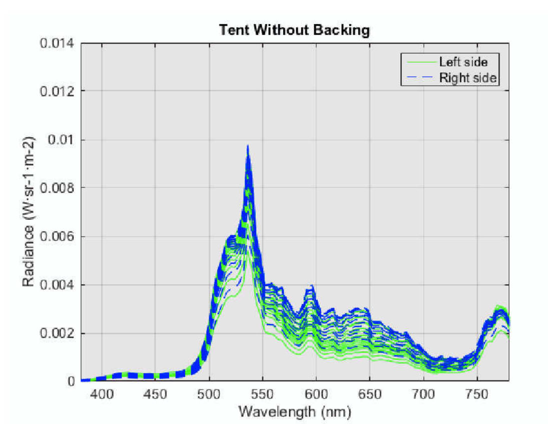

***Figure 7**: Spectral radiance of the tent sample with no backing.*

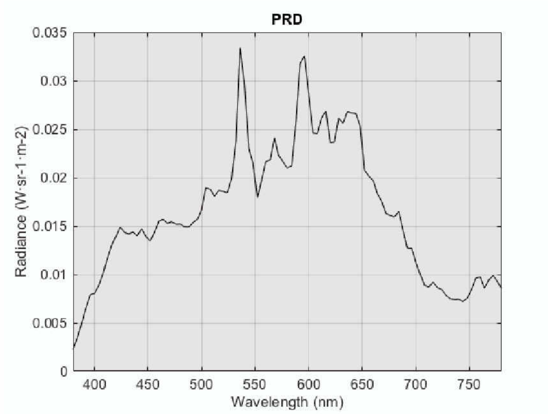

***Figure 8**: Spectral radiance of a PRD.*

The spectral radiance of the tent sample with no backing and a PRD sample are plotted in Figures 7 & 8. The sample radiance measurements were divided by the PRD radiance measurement to calculate the reflectance factor for each sample.

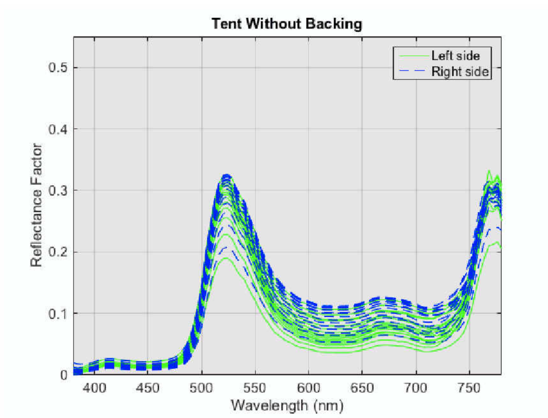

***Figure 9**: Reflectance factor for the 'tent' sample.*

The reflectance factor was used to calculate the CIEXYZ tristimulus values. Tristimulus values were then used to calculate CIELAB values as well as CIEDE2000 color differences for measurements taken at different angles. The color differences between the left and right side for each angle can be found in table 3.

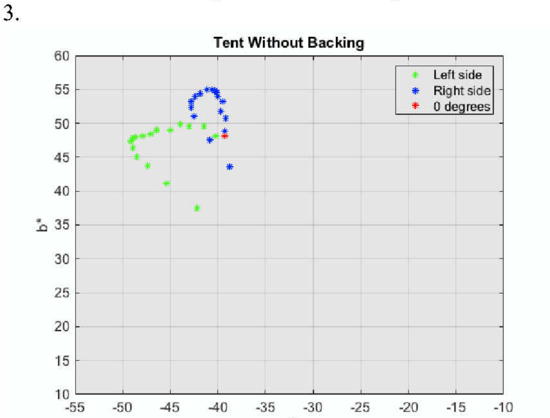

***Figure 10**: Plot showing a*b* coordinates for the tent sample with no backing.*

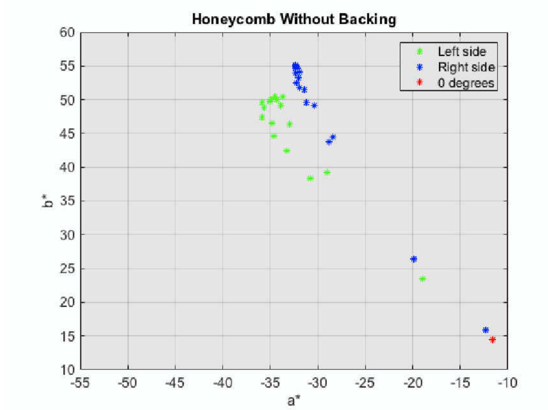

***Figure 11**: Plot showing a*b* coordinates for the honeycomb sample with no backing.*

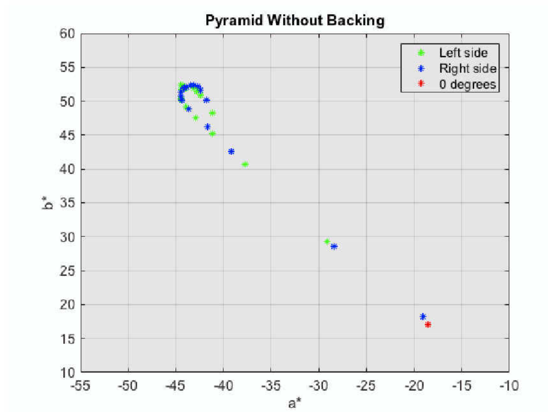

***Figure 12**: Plot showing a*b* coordinates for the pyramid sample with no backing.*

The shapes of these data plots were similar for each of the samples with each of the backings so only one is shown for each sample, which can be found in Figures 10-12. These were quite similar for each of the backings so only one of the measurements are shown here. What is important to note here is the divergence in the shape of the tent and honeycomb samples when viewing them from either the left or right side.

The color differences were calculated for equal but opposite angles of observation measurements on both sides of the samples. For example the difference between 5° to the left of the sample's surface normal was compared to 5° to the right. This was done for each angle measured. Again, these were similar for each backing, so only one has been included. The color differences at the 5° and 10° angles for the honeycomb and pyramid samples are quite large relative to the other differences. They are also unexpected since the color difference should trend upwards as the angles increase. Each of the samples were given a 'quick dry clear coat' which may have resulted in an unwanted glossy appearance. The finish was applied to each of the samples so it is curious that this did not occur with the tent sample and will require further investigation.

Table 3: CIEDE2000 color differences calculated for equal angles between 5º and 80º on either side of the samples.

	No backing		
Angle	Tent	Honeycomb	Pyramid
5	0.62	13.61	14.15
10	1.76	11.85	13.07
15	2.45	3.18	0.46
20	2.99	1.50	0.30
25	3.79	1.25	0.22
30	4.36	1.74	0.39
35	4.87	2.82	0.30
40	5.29	3.67	0.25
45	5.18	2.95	0.20
50	4.82	3.43	0.04
55	4.61	3.85	0.03
60	4.49	4.32	0.15
65	4.44	3.94	0.31
70	4.17	4.08	0.42
75	4.15	4.30	0.70
80	3.96	4.33	1.44

Goniospectrophotometer Measurements

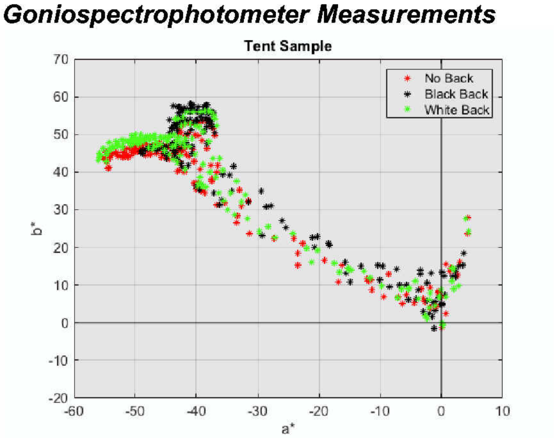

Figure 13*: Calculated a*b* values for the tent sample.*

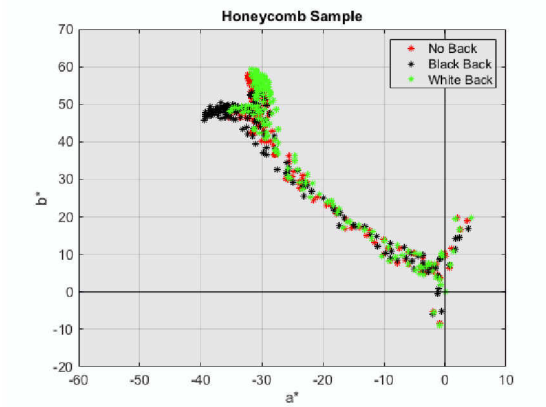

Figure 14*: Calculated a*b* values for the honeycomb sample.*

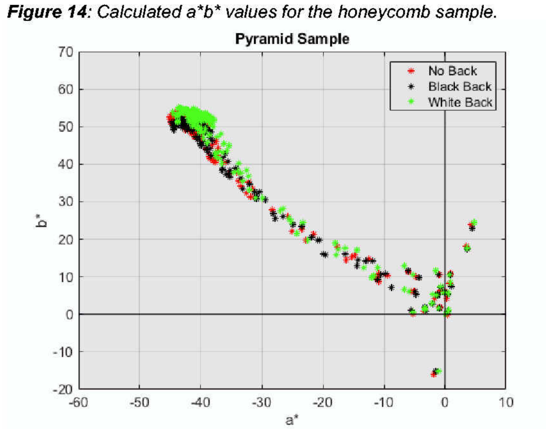

Figure 15*: Calculated a*b* values for the pyramid sample.*

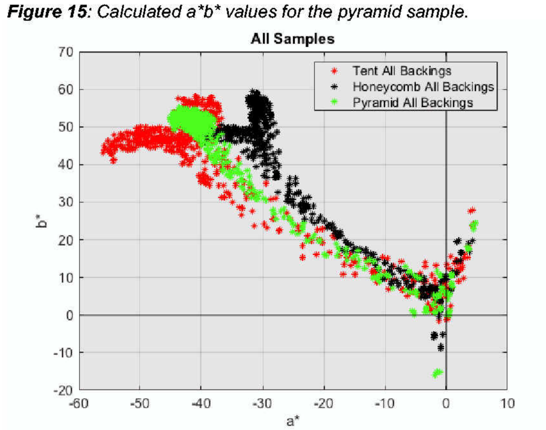

Figure 16*: Calculated a*b* values for all three samples.*

Figures 13 through 15 show the plotted a*b* values of the three samples with the three backings. Measurements were taken by rotating the samples within the goniospectrophotometer, changing the angle of observation. The angle of incident light was varied independently as well. A similar divergence previously observed in the measurements taken with the gonio-arm setup can be seen here for the tent and honeycomb samples. This divergence indicates a color shift from yellow-green to graysh to green-yellow as the angles of observation shifts along the face of the samples. Again, no apparent divergence was observed for the pyramid sample. Figure 16 combines the previous three for visual comparison.

Discussion

The color 3D printed samples did produce measurable goniochromatic effects. The samples printed with different 3D geometries produced CIELAB values that were quite different despite using the same colored material suggesting that manipulating the geometries of color 3D printed objects on a small scale does offer some level of control on the object's appearance.

The divergence along the a* axis of the tent and honeycomb samples imply that the samples should appear greener with a change in the angle of observation as the plotted values extend outward towards the negative. The divergence along the positive b* axis implies that the samples should appear more yellow at the measured observation angles. The pyramid sample had no such divergence implying that the angle of observation would not affect color appearance. These measurements are in line with the author's anecdotal visual inspection of each of the samples, though a psychophysical experiment would be necessary to fully validate them.

The color differences of opposite angles shown in table 3 are noteworthy. The tent sample appears most yellow when viewed from directly above, then appears greener as the sample is tilted to either side including the side with yellow front-facing geometry. The visual appearance is reflected in the color measurements and aligns well with the color difference trend. The color differences increased initially as the angle of observation increased, then decreased around 45° and on. The reason for this trend back towards the 0° measurement is that the Polyjet material used in the prints is somewhat translucent, which affects color appearance at extreme angles of observation. This would also account for the apparent trend towards areas of lower chroma at larger observation angles.

The different backings used also affected the color measurements. In the BRDF measurements in particular the black backing seemed to have the largest effect. The measurements using the white backing and no backing were similar but for the tent sample the black backing seemed to pull the measurements further towards the negative side of the a* and b* axes, while the opposite was true for the honeycomb sample.

Future Work

The next steps on this project include the design and measurement of several more color 3D printed samples. A psychophysical experiment will also be required to validate the color measurements since these effects are meaningless if they are not actually visible to real observers. While the inspiration for this work relies on emerald ash borer visual perception, validation by human observers is important here as it is required for understanding the fundamentals of human color perception for 3D objects and using this to build reliable ICC profiles. Once all samples have been produced and measured and psychophysical results have been evaluated, parameters of most importance for surface appearance characterization can be selected.

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