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Eiríksson, Eyþór Rúnar; Pedersen, David Bue; Aanæs, Henrik

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PREDICTING COLOR OUTPUT OF ADDITIVE MANUFACTURED PARTS

Eythor R. Eiriksson¹, David B. Pedersen² and Henrik Aanaes¹

¹Department of Applied Mathematics and Computer Science

²Department of Mechanical Engineering

Technical University of Denmark

Kgs. Lyngby, Denmark

ABSTRACT

In this paper we address the colorimetric performance of a multicolor additive manufacturing process. A method on how to measure and characterize color performance of said process is presented. Furthermore, a method on predicting the color output is demonstrated, allowing for pre-visualization of parts prior to print. Results show that color prediction can be achieved with an average color difference error of $\overline{\Delta E_{00}^*} = 1.5$ and std.dev $\sigma = 0.75$, with similar order of magnitude as the literature defined threshold for „Just Noticeable Difference” (JND).

INTRODUCTION

Additive manufacturing has been an accepted means of production for the past decade and is a rapidly growing market. Today, additive manufacturing technologies are offering multi-color printed parts in an assortment of different materials[1]. Availability of print per order parts, where customers can supply their own high resolution color textures and geometries, has become a reality¹²³⁴. Therefore, geometry and color quality assurance is required. So far, research focus has been placed on geometrical verification, giving promising results, whereas less effort has been placed on color verification[2][3]. Here we address the colorimetric performance aspect.

When converting 3D color models to the physical domain, through additive manufacturing, the enormous range of color available during modeling is not reproducible by the printer. The complete range of producible colors is known as the printers *gamut*. Any input colors outside the printable gamut will simply be constrained to a gamut boundary color, as illustrated in Figure 2. This is a known problem in the paper printing industry and is normally solved through printer profil-

ing. Printer manufacturers sometimes offer these printer profiles which describe the printers color production capabilities according to a standard defined by the International Color Consortium (ICC).

In order to fully profile a printers color gamut, one would ideally define the input 3D model in terms of the printers native color space (*CMYK*). Unfortunately this is not possible, as color 3D mesh representations are derived from the *RGB* space. This is to be expected, as these data formats are mostly intended for use in *RGB* based devices such as a computer monitor. It is clear that the growing market of color 3D printing calls for a new or updated mesh format. To the authors best knowledge, no color 3D printing manufacturer offers color profiles or color management features. That being said and due to most printers proprietary nature, any color correction needs to be made at the 3D modeling level.

MATERIALS AND METHOD

In order to characterize the gamut of a ZCorp ZPrinter 650, a patched color plate was printed as seen in Figure 1.

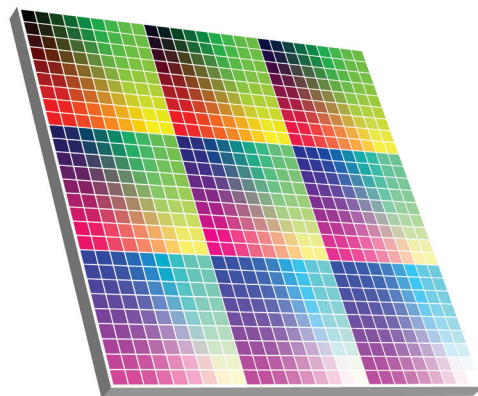


FIGURE 1. 3D model of the color calibration plate, providing 729 unique color patches.

¹shapeways.com

²twinkind.com

³i.materialize.com

⁴figureprints.com

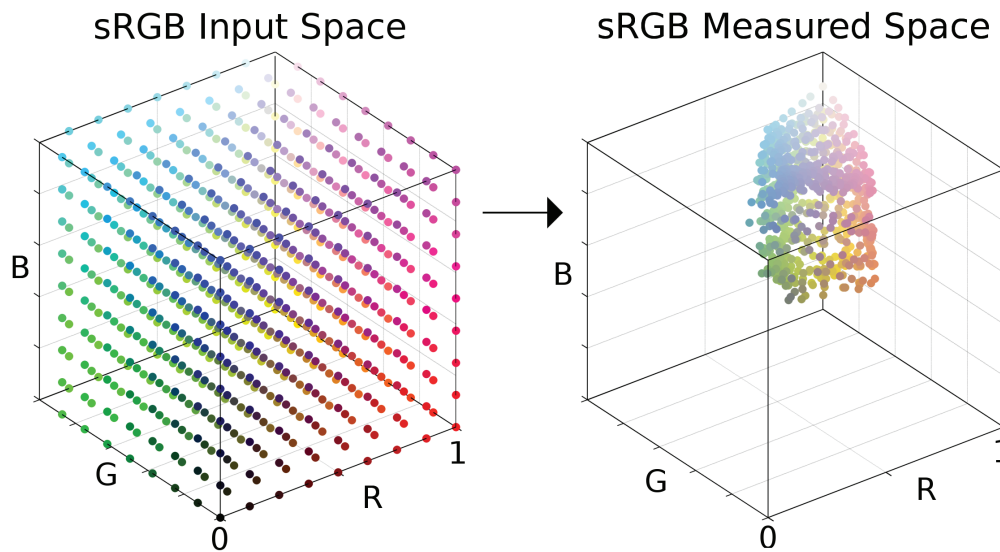


FIGURE 2. Comparison of input *sRGB* values to the actual measured values after print. The printers color generation limitations are apparent. Any colors outside of this printer gamut are not printable.

3D Model Generation

The color plate was generated in the Wavefront `.OBJ` format where each square in the plate was defined with a unique face color. This method was selected over applying a color image texture onto a blank plate. Thus, eliminating all uncertainties of texture handling and mapping in the printer software. The 729 unique color patches were sampled evenly from the entire three dimensional *sRGB* space, as visualized by Figure 2. This $9 \times 9 \times 9$ sample was selected due to physical size constraints set by the color measurement system used. The final plate dimensions are therefore $64.25 \times 64.25 \times 3$ mm with individual patch size of 2.15×2.15 mm.

Print Procedure

In order to capture the variability between prints, a set of 15 plates were printed in a stacked configuration, centered in the build volume. Layer thickness was set to $89 \mu\text{m}$, bleed compensation enabled and the ZP150A powder was used. Special care was taken in thoroughly removing residual powder as to minimize color variations between prints whose effect can be seen in Figure 3. As it is known, infiltrating substances have significant effect on color vibrancy, and therefore the prints were not infiltrated in order to minimize additional variability. Modeling of this effect, dependent on infiltration type is a subject for future work.

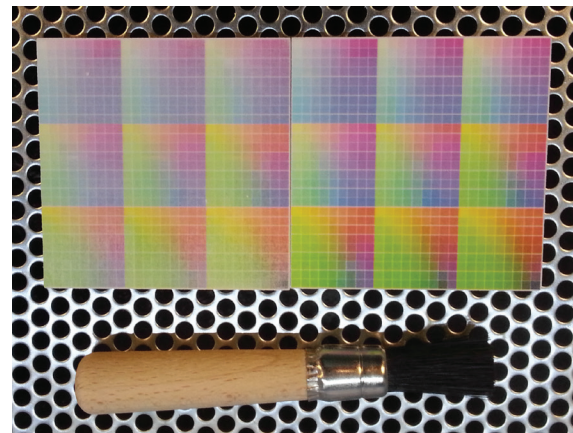


FIGURE 3. Two color plates, before brushing (left) and after brushing (right).

Measurement

Each color patch was measured using the multi-spectral imaging system *VideometerLab2*.⁵ The *VideometerLab2* allows for rapid color capture of an entire plate, contrary to other point sample based color measurement devices such as a colorimeter. Measurements were made in the device independent *CIELAB* color space under the D50 illuminant. Example output from the instrument can be seen in Figure 4. An automated color patch extraction algorithm was implemented

⁵www.videometer.com

and for each colored patch an average color value was computed, ideally simulating the perceptual integration as some color values are printed in dithered like patterns.

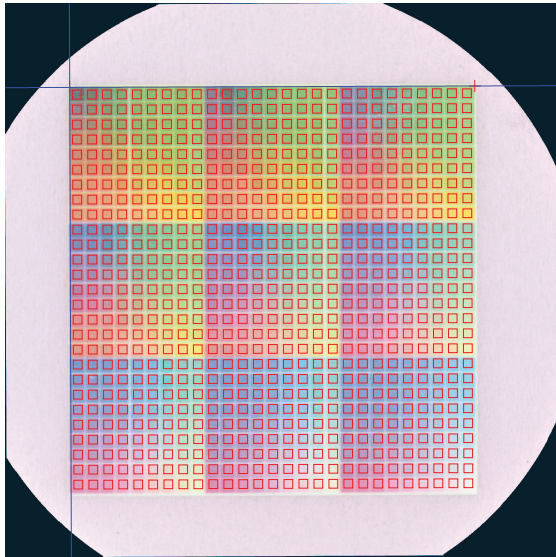


FIGURE 4. Automated patch extraction algorithm collects patches and computes their average color value.

RESULTS

An average plate was computed from all of the 15 measured plates. The color difference metric ΔE_{00}^* from the average color was computed for each color in the *CIELAB* space[4]. The color difference distribution from the mean for each plate is shown in Figure 5.

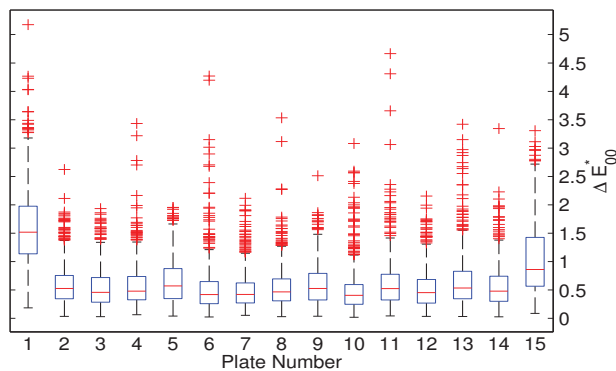


FIGURE 5. Boxplots illustrating color difference ΔE_{00}^* from the group mean. Median value is shown as a line in each box; Box edges are the 25th and 75th percentiles; Whiskers extend to the most extreme data points not considered outliers; Outliers are plotted individually.

It is apparent from the figure that the first and last plates in the stack differ significantly and are therefore omitted from the model. Further study is needed in order to evaluate whether this is a reoccurring trend. Figure 2 shows the transformation from the input *sRGB* values and the measured values. It is clear that the printer is not capable of printing a large majority of the input colors. Figure 6 clearly shows the printers inability to produce darker colors and the average color error is $\overline{\Delta E_{00}^*} = 21.4$, std.dev $\sigma = 4.15$. Several studies have tried to estimate the Just Noticeable color Difference threshold (JND) of the ΔE_{00}^* metric, however many are in disagreement. Documented JND threshold values range from 1 to 5.9[5]. The average systematic error was estimated by repeatedly measuring the same plate several times and an identical analysis performed. The measured systematic error difference was $\overline{\Delta E_{00}^*} = 0.11$ and std.dev $\sigma = 0.07$, orders of magnitude lower than the variations between prints.

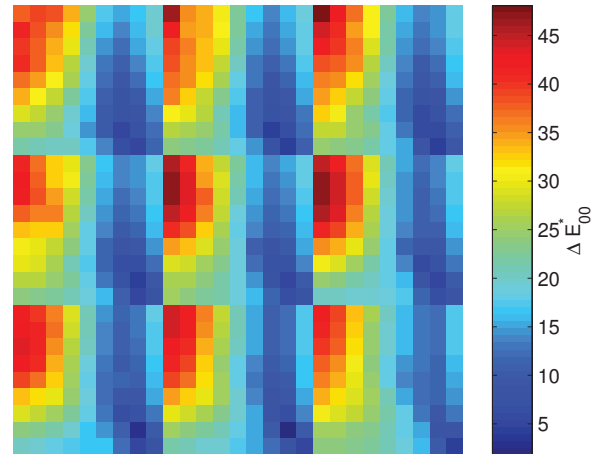


FIGURE 6. Color difference between the ideal plate and an average of the measured plates.

From the average color plate measurements, a 3D Look-Up Table (3D LUT) was constructed relating the input *sRGB* space to the measured *CIELAB* space. The input LUT is essentially a 3D lattice structure where each lattice corner contains *CIELAB* measurement data. From there, any intermediate points within a single lattice cube can be estimated using trilinear interpolation. This 3D LUT model can thus be used to predict resulting color measurements of a printed object given an input color. 3D LUTs are commonly used for this color conversion purpose and can be efficiently implemented on modern hardware.

MODEL EVALUATION

A week after the initial prints were made, a color plate as seen in Figure 7 was generated with random color values. A print prediction was performed using the 3D LUT model and the plate was printed using identical procedures as before. Post print, the plate was measured and compared to the predicted output. The color difference from the prediction obtained from the 3D LUT model and the measured plate is illustrated in Figure 8. The computed error mean was $\overline{\Delta E_{00}^*} = 1.5$ with std.dev $\sigma = 0.75$.

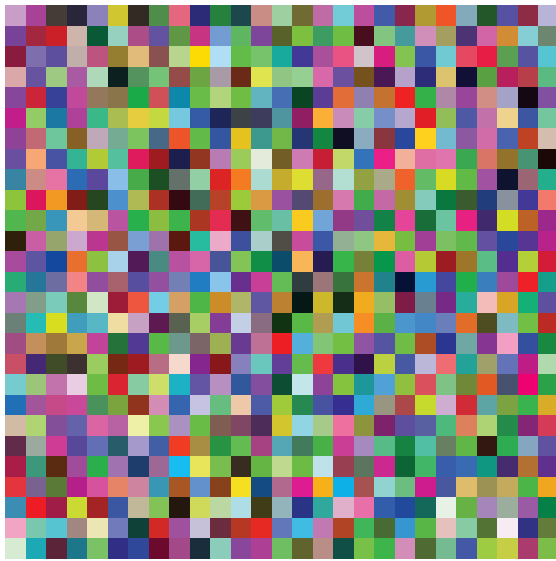


FIGURE 7. Plate with randomly generated colors, used for model verification.

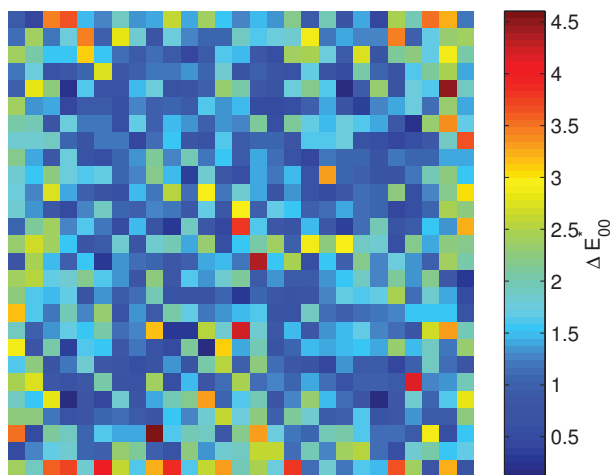


FIGURE 8. Color difference between prediction and actual measurements of the random plate.

DISCUSSION AND SUMMARY

The method described in this paper has been applied on an inkjet based 3D printer. Its variability and color limitations were visualized. When looking at the group statistics of the plates we observe the bottom and top plates to be statistically different from the rest. For the plate located in the bottom, we have two hypotheses. Firstly, the powder in the build chamber might not be compact enough in the bottom prior to print, thus yielding different surface textures. Secondly, the print head might not have reached a steady state of operation so early in the print. For the top plate, we believe it might be a factor of powder compression and drying as only a few extra layers of powder are deposited over the last plate. The remaining plates were measured using a multi-spectral imaging system with determined average systematic color measurement error of $\overline{\Delta E_{00}^*} = 0.11$ and std.dev $\sigma = 0.07$. Upon comparing the input data to an average of the measured data it was apparent that a large part of the input colors was not printed to specification. In fact, the average color error was $\overline{\Delta E_{00}^*} = 21.4$, std.dev $\sigma = 4.15$ and maximum color error greater than 45. Significantly exceeding the literature defined noticeable color difference threshold which ranges from 1-5.9. The largest error contribution was from the darker colors, particularly in the absence of red and green. These error regions are expected to somewhat heal by infiltration, where darker regions are known to benefit greatly. However, this might come at the price of the more lighter colors, as white will appear more grayish. A 3D Look-Up Table was constructed relating the input color values to the empirically measured color values. This allowed for a simple and efficient way to perform a color prediction given an input color value. If an input color value was not present in the table, trilinear interpolation was performed from the known values, yielding a color estimate. To evaluate the prediction model, a new color plate was generated consisting of randomly generated color patches. It was printed on the same printer and finally compared to the generated prediction model. The model captured the color conversion well with reasonable accuracy and an average color difference error of $\overline{\Delta E_{00}^*} = 1.5$ with std.dev $\sigma = 0.75$. This result lies within the noticeable color difference threshold range, making this method a promising candidate for color correction. Some error contribution is due to interpolation of color values, to which extent is unknown. The effect could be minimized by an even greater

sampling of the input color space. An important aspect of this study lies in the fact that the model and model verification was performed at a weeks interval, whilst the printer underwent normal use. It is therefore, interesting to see the stability of the print process and that the model holds, making this a candidate for longer term production runs utilizing the current setup.

FUTURE WORK

Reverse modeling methods will be attempted, relating the *CIELAB* output space to the *sRGB* input space. Color correction could thus be applied to the 3D modeled part prior to print. Furthermore, a further statistical analysis on the error components will be conducted.

ACKNOWLEDGEMENT

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⁶www.made.dk