DESIGNING FOR COLOR IN ADDITIVE MANUFACTURING

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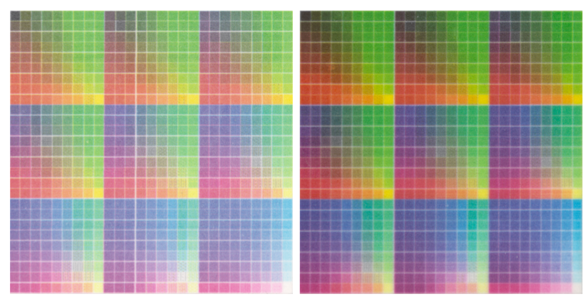
ABSTRACT
In this paper we present a color design pipeline for 3D printed or additively manufactured parts. We demonstrate how to characterize and calibrate a commercial printer and how to obtain its forward and backward color transformation models. We present results from our assistive color design tool, allowing for colorimetric accurate prints and visualization of the printed outcome, prior to print. Lastly, we demonstrate our pipeline by accurately reproducing a real physical object.

INTRODUCTION
Due to physical constraints in the 3D color print process, it is impossible to print parts in all colors that we are presented with in the digital domain. The rich saturated colors are simply not available with current printer technology. Failure to acknowledge this limitation results in both disappointment and dull prints. The paper printing industry has been dealing with these problems for decades, still we have yet to see any of the solutions made available for the 3D domain. As of today, no formats supported by the additive manufacturing (AM) printer industry offer CMYK (Cyan, Magenta, Yellow, Black) color inputs, despite it being the native color space of most color printers [1]. Instead, RGB (Red, Green, Blue) is used, as the 3D formats were initially intended for display in RGB based devices, such as computer monitors and televisions.

The transformation from additive RGB colors to subtractive CMYK is handled within the printers hardware. Due to its proprietary nature and lack of color management features, any color related efforts must be made on the 3D model level. A designer is thus designing colored parts in the blind as no relationship exists between the color presented in the computer monitor and the final printed output. Previous efforts focusing on color in additive manufacturing has addressed color placement [2], appearance [3] and attempted to shed light on this problem by modeling the color conversion, thus allowing for color print prediction [4].

In this paper, we take inspiration from the paper printing industry and apply known methods on the new medium. We present a full end-to-end color design pipeline which allows for color specification. The ability to accurately specify colors and appearance of 3D printed objects has applications ranging from rapid product design, printing prosthetics or dentures seamlessly matching their hosts, and for physical replication of objects.



(a) Dry *(b) Infiltrated*

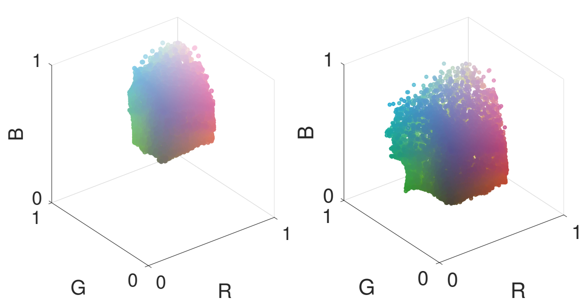
FIGURE 1. Printed color calibration artefacts used in this study.

CALIBRATION
In order to print user specified colors, it is important to understand the color capabilities of the printer. This is obtained by characterizing and modeling the printer's output colors in relation to its input. In this section, we present a calibration method which produces forward and backward color models of the print process. Using the forward model, it becomes possible to previsualize the resulting printed color given any input color. Furthermore, if one wishes to print a specific color, the backward model will return the input color required for producing the desired printed color or the closest available color. The calibration procedure is described in the following steps:

Step 1: Calibration Plates
A 3D color plate was generated which has colors sampled uniformly from the RGB color space. A total of 9 samples were made per dimension, resulting in 729 unique colors. We chose this value due to size restrictions of our color measurement system. Ideally, the more samples used in this process the more accurate the characterization and calibration.

Step 2: Print
Two color calibration plates were printed on a Zcorp Zprinter 650 color printer. The plates were thoroughly brushed in order to remove any residual surface powder. One plate was infiltrated with cyanoacrylate whereas the other was kept dry without any infiltration.

Step 3: Measure
Both plates were measured using the multispectral imaging system VideometerLAB 4[1]. Both CIELab D50 and sRGB D65 measurements were obtained for each color patch using an automated algorithm. Figure 2 illustrates the measured range of printable colors possible. It is clear the color gamut is significantly enhanced after infiltration, however at a slight cost of the lighter colors such as white.



(a) Dry (b) Infiltrated

FIGURE 2. Visualization of the printable color range. (Gamut)

Step 4: Forward and backward model
From the empirical measurements relating input colors to measured colors we construct a 3D look up table (3D LUT) of $9 \times 9 \times 9$ elements. The table is then linearly interpolated up to $256 \times 256 \times 256$, thus covering the 8 bit RGB representation. Using the forward lookup table, it is possible to predict measured colors for all input colors. For the backward model a reverse 3D LUT was made of dimensions $256 \times 256 \times 256$ mapping measured colors to its input. For all colors outside of the printable gamut, the nearest neighbor color value was used. This resulted in an 8 bit 3D LUT which returns a color measurement for all possible inputs. By precomputing the LUTs, it becomes possible to efficiently use them as 3D textures commonly used by the computer graphics community.

Step 5: Verification
In order to verify the forward model, a new color plate was printed consisting of random colors. The plate was measured and the color difference metric ΔE^*_{00} between the model and the measurements was computed for each color in the *CIELAB* space [5]. The results for the dry and infiltrated model can be seen in Figure 3. For the dry plate we obtain an mean prediction error of $\overline{\Delta E^*_{00}} = 1.3$ and std.dev $\sigma = 0.9$. For the infiltrated plate we obtain $\overline{\Delta E^*_{00}} = 1.5$ and std.dev $\sigma = 1.2$. The increase in standard deviation is as expected since additional variability is introduced in the infiltration process. From Figure 3, it is clear that majority of points lie within the documented just noticeable difference (JND) range from 1 to 5.9 [6, 7]. The prediction model is thus considered satisfactory.

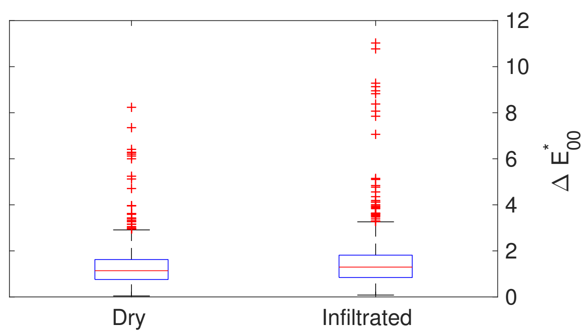
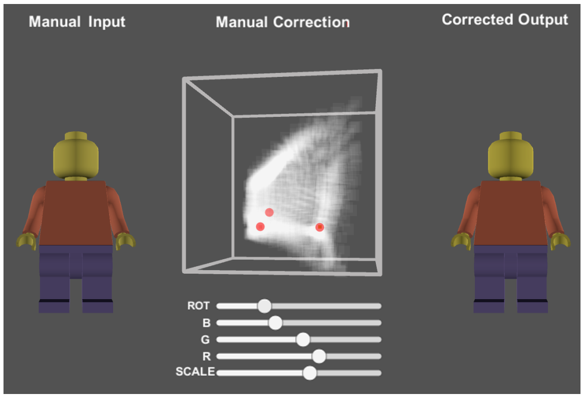


FIGURE 3. Boxplots illustrating color difference ΔE^*_{00} between the measurements and the prediction model. Median value is shown as a line in each box; Box edges are the 25th and 75th percentiles; Whiskers extend to the most extreme data points that are not considered outliers; Outliers are plotted individually.

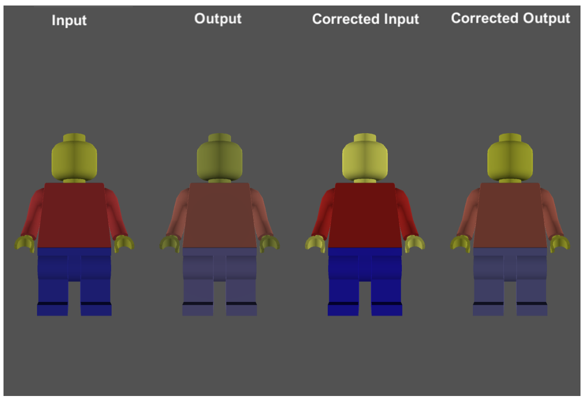
COLOR DESIGN TOOL
After the printer characterization, we used the calibration data to develop a design tool which enables us to pre-visualize parts before print and to perform color correction if needed. The tool has been developed using the Unity-Game Engine[2].

[1] videometer.com

[2] unity3d.com



(a) Manual Mode

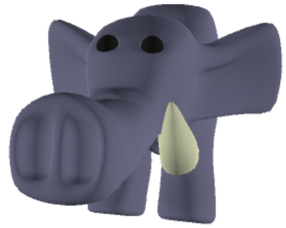


(b) Automatic Mode

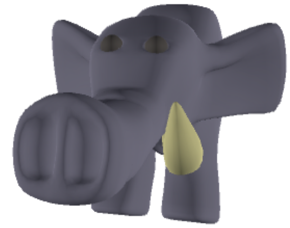
FIGURE 4. Screenshots from our design tool. Showing manual and automatic modes of operation.

Figure 4 shows screenshots captured during operation. The pre-visualization feature makes use of the forward 3D LUT in order to visualize the resulting print of a 3D color model. The reverse 3D LUT is used to perform color compensation on the 3D model in order to account for the change in color due to the print process. Figure 5 shows a toy example for a 3D model of an elephant using the infiltrated 3D LUTs. It is clear that the print prediction of the model (Figure 5b) looks different from the original model (Figure 5a), while after applying the appropriate color compensations the print prediction of the model (Figure 5d) is closer to the original model even though there are still some differences in the colors of the eyes and of the tusks of the elephant.

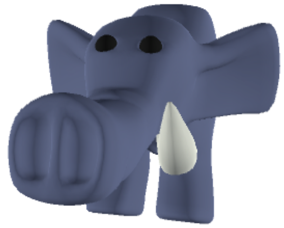
A good color correction can be done only if the colors of the 3D model lie inside the printable color range. Our design tool provides a feature for visualizing which colors of a 3D model are outside the gamut and therefore are not possible to



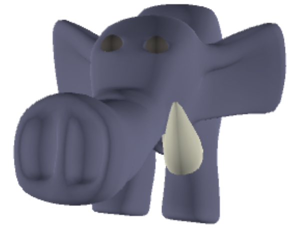
(a) Input model.



(b) Model print prediction.



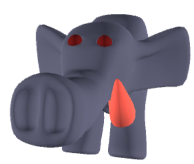
(c) Color corrected model.



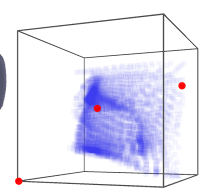
(d) Corrected model: Print prediction.

FIGURE 5. Design tool results (Infiltrated LUTs).

correct by using the measured 3D LUTs. Figure 6 shows the elephant model using the infiltrated 3D LUTs where the colors of the eyes and tusks do not lie inside the printable gamut shown in Figure 2b. As result, they are highlighted with a reddish color. For each color that is not printable, the reverse 3D LUT provides the nearest printable color, and while in some cases, e.g. elephant's tusks, this approximation might give acceptable results in other cases, e.g. elephant's eyes, the corrected color is far away from the original color. In terms of colorimetric accuracy, this might not be acceptable. However, if the goal is to produce visually pleasing results, the tool allows the user to maintain the relative relationship of colors.



(a) Input model. Out of gamut colors highlighted in red.



(b) Gamut and input color visualization.

(c) Print prediction.

FIGURE 6. Design tool output using infiltrated LUTs. Model colors are marked as red dots, whereas the printable region is depicted in blue. On the model, the out-of-gamut colors are highlighted in red, alerting the user that these colors will not be printed correctly.

In order to correct the colors outside of the gamut, our tool gives the possibility to manually change the colors of the model until they all lie inside the printable color range. Then, by performing an automatic compensation based on the forward and reverse LUTs, we can visualize the print prediction of the manually-corrected 3D model. An example of this feature can be seen in Figure 6, where we see a 3D input model with the highlighted out-of-gamut colors, and the resulting print prediction of the corrected 3D model. Additionally the RGB color space is visualized dynamically where the printable gamut (blue region) and the colors included in the original 3D model (red dots) are shown. This gives the user a dynamic visual feedback of how many colors of the input model are lying outside of the gamut and therefore not printable.

The manual color correction is performed by scaling and translating the red dots representing the colors of the input model until they fit inside the region covered by the gamut. This is done interactively using sliders. The colors that are manually placed inside the gamut become printable and the reverse and forward LUTs show dynamically the color correction print prediction of the model as close as possible to the manually corrected input model. A designer thus has full control over the colors in a 'What you see is what you get' (WYSIWYG) fashion, greatly simplifying the design process.

EXAMPLE: PART REPLICATION.
To further evaluate our model and design tool, we measured a sample of cork in order to create a 3D printed replica. Figure 7 shows results from our design tool which given an input 3D color model (Figure 7a), visualizes its resulting print (Figure 7b). The tool then produced a corrected version (Figure 7c) where the infiltrated reverse 3D LUT was used to compensate for the change in color during the print process. For user verification the corrected print prediction is shown in Figure 7d.

The corrected color model shown in Figure 7c was printed on a Zprinter 650, allowed to dry, thoroughly brushed and then finally infiltrated with cyanoacrylate. In parallel, the cork was printed with and without color compensation in various sizes. The final printed output can be seen in Figure 8 where the cork replica with color compensation closely resembles the actual object, whereas the cork without compensation is observably darker.

(a) Original sample as measured. *(b) Original sample: Print prediction.* *(c) Color corrected Sample.* *(d) Corrected sample: Print prediction.*

FIGURE 7. Results from our color design tool. Demonstrating pre-visualization of parts prior to print. c) shows the color corrected sample as would be used as input to a print process. d) shows the end result, which accurately matches the original sample a).

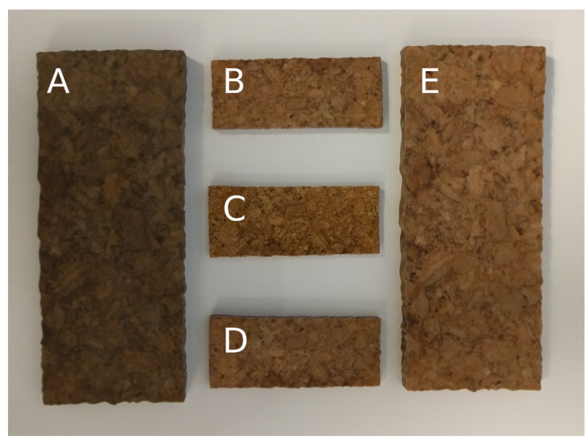


FIGURE 8. Final printed results.
A: Enlarged printed cork without color correction.
B & D: Printed cork with color correction.
C: Original cork sample.
E: Enlarged printed cork with color correction.

DISCUSSION
The process described in this paper has been implemented on an industrial color 3D printer. We demonstrated a successful calibration procedure and a method to verify its validity. The results show that accurate color predictions and calibration can be obtained with color difference error averaging comfortably under the JND metric threshold. We presented preliminary results from our

color design tool that can pre-visualize parts before print as well as apply automatic color compensation based on the calibration models. Furthermore, it offers manual means of correcting for color whilst providing visual feedback to the user in the form of a dynamic print prediction and 3D gamut plot. Lastly, we show an example where we produce a 3D replica of a real physical object. Our results show that with color compensation and careful modeling of the print process it is possible to print accurate color replicas closely matching the original object's appearance. With the help of our pipeline, it is thus possible to specify printed colors accurately. This enables the printing of colored prosthetics or dentures seamlessly matching their hosts as well as delivering true and accurate prints of designs during product development.

The design tool will be made publicly available in the near future.

ACKNOWLEDGEMENT

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