

# Multi-Layer Halftoning for Poly-jet 3D Printing

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## Abstract

*Accurate color reproduction is an essential parameter in many 3D printing applications. Although current technologies in full-color 3D printing have enabled the reproduction of thousands of colors, reproducing the precise target color is still challenging and requires tuning. In this paper, we integrate halftoning with a multi-layer printing approach, where ink is deposited at variable depths, to improve the reproduction of tones and fine details in poly-jet 3D printing. The proposed approach is implemented using a manually controlled ink placement add-on for a commercial 3D printer and is compared to the default software of that printer. Results demonstrate that the proposed multi-layer halftoning performs more accurately in reproducing the tones and details of the target appearance.*

## Introduction

Additive manufacturing technologies refer to the fabrication of a 3D object by stacking up several layers of materials. The introduction of full-color 3D printing technology, e.g. poly-jet 3D printing, enables the reproduction of complex 3D objects with a wide range of colors and textures. Unlike traditional 3D printers that can only produce single-color objects, 3D color printers use ink-jet printing techniques to apply colored inks layer by layer.

Poly-jet 3D printing is a promising technology for 3D full-color printing, but there are still hurdles in the way of getting an accurate color reproduction [1]. Despite the fact that full-color 3D printers can produce thousands of distinguishable color combinations, improving color accuracy and increasing the color gamut are still challenging [2]–[6]. Without accurate color reproduction, achieving visually appealing and realistic 3D printed models is difficult. Many studies have been conducted to improve the color reproduction in full-color 3D printers. For example, it has been shown that applying colors only to surface voxels (outermost layer) results in a very low-contrast output where the printed object fails to represent the target appearance [3], [6]. However, increasing the depth of color assignment results in material mixing and light scattering, therefore leading to color bleeding [2]–[6]. Hence, to fully achieve the target appearance, the color assignment within the object's volume needs to be optimized.

In this paper, we aim at improving tone reproduction and preserving fine details in poly-jet 3D printing. We study the effect of varying the number of halftoned layers at each voxel on the accuracy of tone reproduction. We develop a method which combines halftoning with a multi-layer printing approach similar to color contoning [2], and finds a balance between the number of layers that must be halftoned and accurate tone reproduction. We use the 3D Iterative Method Controlling the Dot Placement (IMCDP) halftoning algorithm [7] to halftone patches and determine the dot placement using white and black inks to obtain the desired gray levels. Simulations have shown that the 3D IMCDP halftoning algorithm generates high-quality reproduction for all gray tones [7]–[9], however, the method has not been employed

in a real 3D printing pipeline and this work is the first effort that applies 3D IMCDP to 3D printing experiments.

As the depth of material assignment varies at each voxel, our approach differs from the 3D halftoning introduced by Brunton et al. [6]. Our method controls ink positioning at variable depths and less ink is jetted into the volume of the object, therefore, not only is the unwanted material mixing reduced but also the ink consumption is decreased. Moreover, taking advantage of halftoning, our proposed method is not as computationally exhaustive as color contoning [2], [4], and in contrast to Elek et al.'s method [3], we do not require structural gradients information to adjust the material distribution. We evaluate our method using the manual voxel printing utility of the J55 Stratasys 3D printer and compare it to the default software's output.

## Related Work

To guarantee the applicability and visual appeal of 3D-printed objects, accurate color reproduction and preserving fine details are crucial tasks in 3D color printing. Many researchers have addressed the inevitable negative causes that make precise 3D tone reproduction challenging. These challenges stem from a range of causes that go from the optical properties of the build material, all the way to the parameters of the printing process. For example, in the poly-jet 3D printing process, to ensure the structural integrity of the print, voxels are overlapped in the *XY* plane. A roller or a squeegee presses the height (*Z*-level) to flatten the print and enforce the voxel's cohesion in *Z*-direction [10]. Thus, voxels are not completely independent and material contamination between neighboring voxels in all directions is unavoidable. Moreover, material mixing within the inner voxels prior to UV-curing, mixing of build and support material at surface voxels (especially on vertical surfaces), and remaining support material, which cannot be fully removed through post-cleaning, pollute the surface finish and result in inaccurate color reproduction [3], [5], [6], [11]. In addition to limitations due to the printing process itself, other adverse effects are caused by the optical properties of printing materials, such as light diffusion and subsurface scattering that lead to a blurry and undesirable appearance [2], [3], [5], [6].

Many of the recent studies aimed at compensating such unfavourable effects to improve the reproduction of custom and accurate appearance in multi-material full-color 3D printers [2]–[6], [11]–[13]. In this section, we briefly review those which are closely related to our work. Brunton et al. [6] brought up the fact that not all voxels in a 3D shape need to be processed, and placing materials only within a distance from the surface result in an accurate reproduction of color and details. They made a trade-off between the computational complexity and the achievable gamut volume and applied their halftoning to the depth of 12 layers. Applying halftoning to a limited number of layers not only minimized the resulting translucent appearance, but also reduced the computational complexity.

Babaei et al. used MultiFab [14], a laboratory-scaled multi-

material ink-jet 3D printer, to find the best ink mixing ratio to achieve accurate color through color contouring. Color contouring stacks up layers of inks to achieve a desired color using a layering approach. Shi et al. improved the color contouring method by using a pair of neural networks to predict the color of ink stacks and find the best combination of inks that reproduces a given color. However, their models outputted a continuous-value prediction of the amount of ink stacks, where they took advantage of the error diffusion halftoning technique to discretize it to an integer number of layers for practical printing [4].

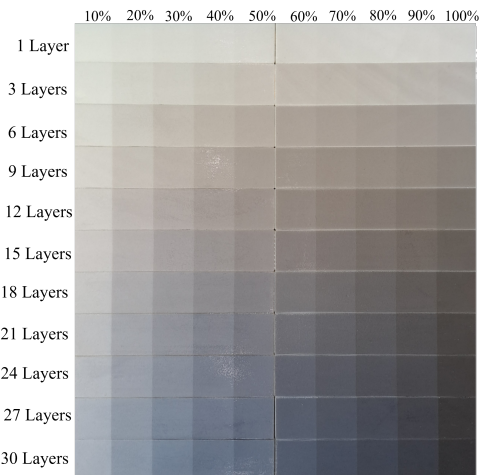
Elek et al. used a scattering-aware volumetric optimization method and structural gradients to assign materials at different depths such that the higher-absorbing materials are embedded closer to the object's surface [3]. They showed that their proposed color reproduction method reproduces high-frequency features better than the default printer output. Their approach was later extended by Sumin et al. to achieve a geometry-aware color gamut to reproduce complex arbitrary geometry [5].

## Methodology

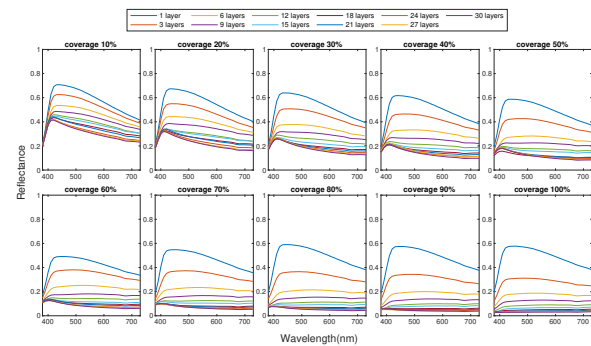
We printed patches with different shades of gray going from 10% to 100% coverage, in steps of 10% and applied halftones to 1, 3, 6, ..., 30 layers (with steps of 3). Layers have been halftoned independently. Figure 1 shows the set of printed patches (110 patches) we used in this work. As can be seen in this figure, applying halftones to a different number of layers affects the reproduced tone. However, the difference is not easily distinguished for layers above 24, and the tone starts to saturate. To accurately find the saturation point, we measured the spectral reflectance of each patch using an X-Rite i1 Eye-One spectrophotometer. Figure 2 shows the reflectance factors plotted at wavelength intervals from 380 nm to 730 nm. According to the reflectance curves, for the current printing settings, the reproduced tone saturates at 24 layers. In other words, increasing the number of halftoned layers, or assigning colors deeper than 24 layers, results in negligible or no tone difference. On the other hand, applying halftones only to a small number of layers does not reproduce the desired contrast. For example, halftoning only one layer, makes the tone difference between neighboring patches barely visible (the first row of the samples in Fig. 1). By increasing the number of halftoned layers, a wider range of tones is reproduced, however, the black point is not achievable at full coverage with a small number of halftoned layers. This could be inferred through visual evaluations of printed samples in Fig. 1 or the reflectance factors in Fig. 2.

One can think of using a higher number of layers to ensure achieving saturated colors and the darkest black point. However, as can be seen in Fig. 1, increasing the number of halftoned layers worsens the tone reproduction in light tones. Although we have only used black and white materials and expected to reproduce neutral shades of gray, with a greater number of halftoned layers, light-tone patches start to appear bluish. This is clearly visible in printed patches in Fig. 1 and reflectance curves in Fig. 2. It is worth noting that we measured the samples with both UV-included (M0) and UV-excluded (M2) modes, and we did not observe any difference in the spectral reflectance response, which dismisses the hypothesis of the presence of a fluorescence effect.

To have a better presentation of the effect of applying halftones to a different number of layers, we mapped an image of VanGogh onto a simple 3D shape and halftoned the entire model with a constant number of layers. Figure 3 illustrates the printouts. As can be seen, as the number of halftoned layers



**Figure 1.** Printed patches with different concentration of black ink on white material (from 10% to 100% coverage) halftoned up to multiple number of layers (1, 3, 6, ..., 30 layers). Size of each small flat patch is  $2 \times 2$  cm.



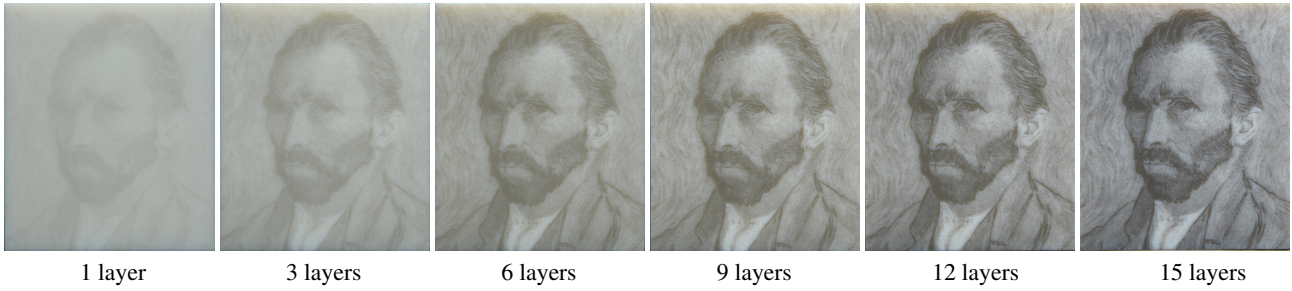
**Figure 2.** Measured spectral reflectance factors of printed patches shown in Fig. 1.

increases, the contrast improves, however, at 15 layers, the undesirable color shift starts to appear in lighter tones. For example, the white shirt appears bluish. Applying halftones to a constant number of layers throughout the entire print without considering the target tone value at each particular voxel does not create a faithful appearance. The resulting appearance either fails to present the desired contrast or suffers from color shift. In the following section, we describe our proposed method to find an optimal number of halftoned layers per voxel to reproduce accurate neutral gray tones with fewer halftoned (inked) layers.

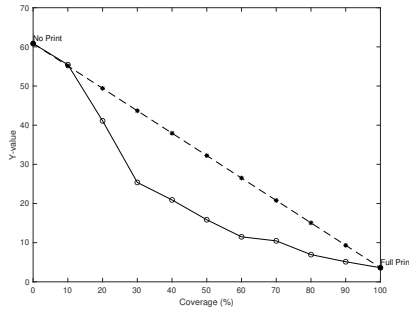
## Proposed Method

The challenge is to find the balance between the number of halftoned layers and ink coverage to reproduce accurate colors with fewer halftoned (inked) layers. We need to optimize the number of layers being halftoned for every intensity level to achieve the desired contrast while avoiding the appearance of a bluish tint in light tones. In this work, we use a simple, yet efficient, method to vary the number of halftoned layers at each voxel based on the initial tone of each surface voxel.

According to Fig. 1 and 3, halftoning only one layer does not reproduce the favourable contrast, and tones start being visible at three halftoned layers. Moreover, it has been shown that increasing the halftoned layers improves the reproduction of darker colors, however, halftoning more than 24 layers results in negligible color difference. Therefore, we set the lowest and highest limit for the number of halftoned layers to 3 and 24, respec-



**Figure 3.** Effect of applying halftones to a fixed number of layers within the entire model. Increasing the number of halftoned layers improves the contrast.

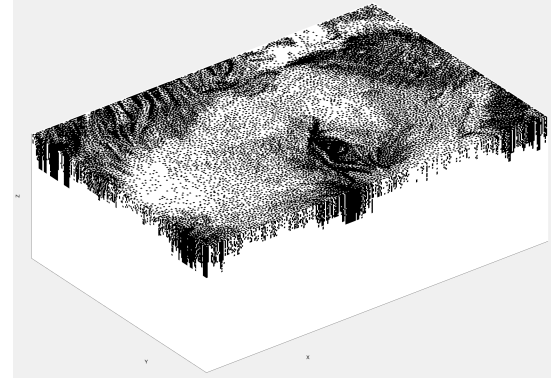


**Figure 4.** Y-values of the target tones between 0% and 100% coverage of black ink on white material using two approaches: a linear interpolation (dashed line) and decreasing the luminance (solid-line). All color coordinates reported in this paper are converted based on D65 reference white point.

tively, and define a simple method to apply halftones to a different depth at each voxel. First, we defined the white material as the target white point ( $L^* = 82.30, a^* = -4.81, b^* = -6.07$ ) and 24 layers of full-coverage of black ink as the target black point ( $L^* = 22.29, a^* = -0.03, b^* = 1.49$ ). Measurements were done using a spectrophotometer with a 2-degrees geometry under D65 illuminant. We assumed that these CIELab values correspond to the maximum white point and minimum black point achievable with current white and black materials. Next, we defined a set of 11 target shades of gray at steps of 10% (achievable by the current white and black materials) through linear interpolation of the target white and black point in CIEXYZ color space. Once we defined target colors, we searched over 80 patches (from 3 layers to 24 layers) for the patch that matches the target tone specification based on the minimum color difference using CIEDE2000 [15].

Defining target tones linearly distributed within the range of the target white and black points did not result in faithful tone reproduction as the printout was too bright. Thus, we opt to redefine target tones with a lower luminance (smaller Y-value). Figure 4 shows Y-values defined for target tones using linear interpolation and modified improved target tones. For the current printing settings, it was empirically found that defining target Y-values as the solid-line in Fig. 4 reproduced the target appearance more accurately than the linear interpolation shown as the dashed-line in this figure. It is worth noting that only the Y-value was redefined, and X-values and Z-values still are linearly interpolated within the range of the target white and black points.

Considering that the input tone is scaled in the range of [0,1], (with 0 being the lightest and 1 the darkest input tone), our methodology of defining the target tones and searching for the minimum color difference using CIEDE2000 results in halftoning a different number of layers per voxel that is deter-



**Figure 5.** Visualization of halftoning different number of layers within a single print. In light-tone regions, a smaller number of layers are halftoned compared to dark-tone regions.

mined according to the initial tone being mapped on each surface voxel. Table 1 summarizes the relation between the number of halftone layers and the input tone used in our proposed multi-layer halftoning.

It is worth noting that defining the target tones is an important aspect of this method. Changing the target tones (or the Y-values shown in Fig 4), may result in a different combination of layers for input tones in the proposed multi-layer approach, therefore, the final printout may present a different appearance, which does not necessarily result in an improvement. Figure 5 illustrates a cross-section of the proposed multi-layer halftoning technique being applied on VanGogh's portrait as the initial tone mapping.

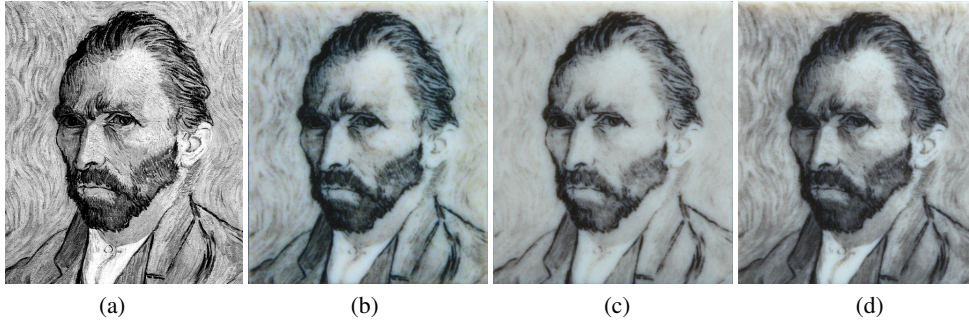
### Printing Setup

In this work, we used the Stratasys J55 poly-jet printer, and its software platform, GrabCAD, which has a Voxel Print Utility as a software add-on, allowing users to bypass the default settings of the printing software and define a customized material assignment at each individual voxel. Voxel Print Utility is crucial for our application because we aim to apply a customized halftoning technique and control the material placement at different layers. GrabCAD does not generate slices from a 3D model, hence, we made the 3D model, halftoned it, and created slices in MATLAB. Each slice is a .PNG image, and the correlation between the dimensions and number of slices with the printout size is determined by the printer's resolution in the  $x$ ,  $y$  and  $z$  axes. The resolution of the J55 in the  $x$  and  $y$  axes (width and length) is 300 dpi, meaning that each pixel in the .PNG image corresponds to 0.08 mm in the  $x$  and  $y$  directions. The height of the printed model is determined by the number of slices. The J55 prints each layer with a thickness of 18,75  $\mu\text{m}$ . All models printed in this work consist of 270 slices, as a result, the height



**Table 1. Combination of different number of halftone layers based on the initial tone being mapped at each voxel.**

Initial tone of voxel	[0,0.1)	[0.1,0.2)	[0.2,0.3)	[0.3,0.4)	[0.4,0.5)	[0.5,0.6)	[0.6,0.7)	[0.7,0.8)	[0.8,0.9)	[0.9,1]
Number of halftone layers	3	6	9	12	12	15	15	18	21	24



**Figure 6.** Evaluation of the proposed method compared to the default printer's output. (a) Original image, which is mapped on the 3D models, and is considered as the target appearance. (b) 3D printed output using the default software (GrabCAD) of the printer. (c) 3D printed output, using the proposed multi-layer 3D IMCDP and the linearly distributed target tones (Y-values based on the dashed-line plot in Fig. 4). The printout is brighter than the target appearance. (d) 3D printed output, using the proposed multi-layer 3D IMCDP and the target tones with Y-values shown as the solid-line plot in Fig. 4.

of each model is approximately 5 mm.

## Results and Discussion

After determining the optimal number of layers to be halftoned for each input tone at the surface voxel level, we evaluate the proposed algorithm using the Voxel Print Utility add-on of GrabCAD and compare the result with the output of the default method of GrabCAD software. We printed two models using the proposed multi-layer 3D IMCDP with different target colors as described in the methodology section, one using linear interpolated Y-values in the target tones and one with the modified Y-values, shown in Fig. 4. We printed a control model, using the default printing software parameters and UV mapping the image of VanGogh on a 3D model. Once printed, the printouts were captured using a Nikon D850 camera, under D65 illumination conditions. The printouts are illustrated in Fig. 6.

Figure 6 (a) illustrates the target appearance. Figure 6 (b) shows the output of the default software. The default software uses all 5 inks of the J55 printer: Cyan (VeroCyan<sup>TM</sup>), Magenta (VeroMagenta<sup>TM</sup>), Yellow (VeroYellow<sup>TM</sup>), Black (Vero Black Plus<sup>TM</sup>), White (Vero Pure White<sup>TM</sup>) and we do not have control over selecting print materials. These inks are from the VeroVivid<sup>TM</sup> family of inks. This family of inks is characterized by its translucency, although it is less present in the black and white inks of this family. However, it is important to note that the white ink is highly scattering (especially sub-surface scattering). Figure 6 (c) and (d) present outputs of the proposed multi-layer 3D IMCDP with the GrabCAD Voxel Print Utility, where, we only used black and white ink for printing.

Printouts in Fig. 6 (c) and (d) are printed using the proposed multi-layer halftoning, the only difference is in defining the target colors. In Fig. 6 (c), we used linearly interpolated Y-values for the target tones as shown in the dashed-line plot in Fig. 4, while in Fig. 6 (d), we used Y-values for the target tones as shown in the solid-line plot in Fig. 4. Comparing two printouts in Fig. 6 (c) and (d) suggests that determining an optimal balance between the number of halftoned layers and the target tone is essential for accurate tone reproduction and preservation of structural similarity. This is illustrated in the lack of details in Fig. 6(c), mostly in the background. However, in Fig. 6 (d) the tone and details of the target image (Fig. 6 (a)) are better reproduced.

Comparing the optimized printout in Fig. 6 (d) with the de-

fault printout in Fig. 6 (b) shows that the proposed method preserves the target appearance more faithfully in terms of tone and details reproduction. The proposed method minimizes color shift and generates the gray tones of the target image more neutrally. The loss in some details for the reproduction using the default GrabCAD software (Fig. 6 (b)) may be the result of a halftoning technique which does not generate as well-formed halftones as the 3D IMCDP. Furthermore, the fact that the GrabCAD reproduction uses a higher number of halftone layers, as well as employing five different inks, will result in more color-mixing, which in turn affects the tone reproduction quality. However, in the proposed method, the undesirable color mixing within the object's volume is reduced by applying halftones to different depths in a variable fashion. It is also worth noticing that all the printouts appear blurry to different extents, which is probably due to the scattering nature of the VeroVivid<sup>TM</sup> ink family, especially the white ink.

The proposed method for 3D printing requires optimization based on surface geometry, orientation, and ink type. Because the resolution of printers is anisotropic in x, y, and z directions, the depth of ink deposition (in  $\mu\text{m}$ ) vary based on the orientation of the surface being printed. Hence, it is important to adjust the number of inked layers according to the printer's resolution. Also, more support material is placed on vertical surfaces compared to horizontal planes. The accuracy of the results is affected by the geometry of the printed shape, and further investigation is needed to determine the optimal number of halftoned layers for different inks and adjustments based on geometry and print orientation.

## Conclusion

In this work, we presented an approach that improves the reproduction of tones and details in poly-jet 3D printing. The method finds an optimal material assignment within the 3D-printed object's volume through a multi-layer halftoning technique. The number of halftoned layers at each voxel is variable, therefore, not only the unwanted material mixing is reduced, but also less black ink is consumed. Moreover, taking advantage of halftoning, our proposed method is not computationally costly. We evaluated the results using the Voxel Print Utility of the J55 Stratasys 3D printer and compared it to the default software's output. Results demonstrated that the proposed method repro-

duces tones and details more accurately than the default software of the 3D printer.

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