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# A Soft-proofing Workflow for Color 3D Printing - Addressing Needs for the Future

***Ingeborg Tastl*, Miguel A. Lopez-Alvarez**, Alex Ju*, Morgan Schramm**, Jordi Roca***, Matthew Shepherd*****
**** HP Inc. Laboratories, Palo Alto, CA, USA; **HP Inc., Vancouver, WA, USA; ***HP Inc., Barcelona, Spain***

## Abstract

*With the advent of more sophisticated color and surface treatments in 3D printing, a more robust system for previewing these features is required. This work reviews current systems and proposes a framework for integrating a more accurate preview into 3D modelling systems.*

## 1.0 Introduction

3D Printing refers to processes in which material is joined or solidified under computer control to create a three-dimensional object, with material being added in stages (e.g. liquid molecules or powder grains being fused together). Printed objects can be almost any shape and are typically produced using digital model data from a computer-aided design (CAD) model or an Additive Manufacturing (AMF) file. There are many different types of 3D printing technologies such as stereolithography (SLA) [1], or fused deposition modelling (FDM) [2]. They all create a 3D object by successively adding material layer by layer.

There are several commercial 3D printing technologies that can produce full-color realistic objects: The ProJet 660Pro and the ProJet 860Pro from 3D Systems [3] are two examples which use CMYK inks. Stratasys's J735 and J50 [4] have a wide range of materials that are either opaque or transparent. Finally, HP Inc. has announced the HP Jet Fusion 500/300 Series 3D printers [5] which will create full spectrum color parts with a voxel control system resulting in full color functional parts while maintaining optimal mechanical properties. This system enables users to produce both parts to be used for prototyping and final functional parts on the same device. The printers are a core element of an additive manufacturing pipeline. Obviously in this case the requirements for both geometric and appearance accuracy and repeatability become more stringent. In contrast to prototyping, where a 3D printed part "just" needs to approximately convey the "look-and-feel" of the final parts, which will typically be manufactured with other technologies, final parts manufactured with 3D printing need to have the desired mechanical and appearance properties. The degree of accuracy naturally depends on the specific application.

Modern computer-aided (CAD) software tools (e.g. [6-11]) enable consumers as well as professional product designers to create sophisticated models of 3D objects. Originally, the focus was on the geometry and on the mechanical properties, but with the advancement of voxel-controlled full-color 3D printers and an increasing amount of available materials and post-processing techniques, the software tools must provide the capability to define the desired appearance of an object: This process can be as simple as specifying one or more desired colors, or in a more sophisticated application spatially varying color. A user might also want to define surface appearances such as gloss. The most detailed renditions can convey various roughness ranges or even 3D texture like a piece of unfinished wood. Yet another appearance attribute could be the degree of translucency exhibited in materials like marble, wax or porcelain. All those appearance attributes need to be definable in the software modelling tools in a user-friendly way, they need to be producible with the 3D printing technologies, and finally, to make the whole process efficient, they need to be visualized on a monitor and be customizable in the modelling software.

In parallel to the long development of 3D printing technologies, which has now been ongoing for more than 30 years, computer graphics algorithms have become more and more sophisticated, resulting in photorealistic computer-generated images, videos and movies that often can't be distinguished from photographs of real-world scenes. Advertisements for new products like cars are more often computer-generated than photographed. It is just more cost-effective, can be done early in the product development cycle and can easily be optimized for all kind of aspects. Other examples are animated movies, virtual and augmented reality and gaming [12].

The concept of rigorous soft-proofing is not new, and is integral to existing 2D commercial and industrial digital printing, where accurate print preview is a critical part of the workflow: when creating sophisticated advertisement booklets, wine labels that are printed in the thousands and packaging solutions for luxury goods it is understandable that designers and product owners want to obtain a preview/proof of how their product will look like before placing a large order. Soft-proofing (producing a preview on a display) and hard-copy proofing (producing a physical artifact with a different printing technology and/or different materials meant to be used as a preview) has been a standard practice in Graphic Arts for quite a long time and there are common practices, industry standards, and international standards in place on how to do it [13].

All of that brings us to the core of this paper: In the fast developing field of 3D printing where new printing technologies evolve and a plethora of printing materials and modes are on the horizon, 3D modelling software packages urgently need the capabilities to visualize the appearance of 3D printed and post-processed parts and to enable the users of those software packages to use that information to modify the specified appearance attributes. Color is an easy understandable example: A user needs to be able to communicate in an unambiguous way the desired color. This can be achieved through a color specification in a device-independent color space or through a reference sample like a Pantone color chip. Then, the software needs to know the corresponding printed color if a certain printer, material and print mode is used and how to accurately transform that color into a monitor color. This whole process has been well established in 2D printing and is typically performed with ICC profiles and an ICC framework. It is usually limited to color appearance under a specific illumination, typically D50. Standard ICC profiles [14] can be used to create accurate soft-proofing workflows in 2D printing today. The International Color Consortium (ICC) established a standard format workflow to enable color management between different digital devices more than a decade ago.

This paper discusses one specific example of an implementation of a current soft-proofing workflow designed to be used with HP Jet Fusion color 3D printers. This is the first 3D soft-proofing application delivered. It is a stand-alone application for submitting jobs to the 3D printers. Moving forward it will be desirable to have plug-ins to a whole range of modelling software packages which have the functionality to provide soft-proofs for a range of different 3D printers, materials and modes. The initial version of this application has limited scope. Thus, the paper will also elaborate on a general approach for 3D soft proofing moving forward. It is an important issue not only for our company, but for 3D printing companies in general and most importantly for users of our technologies.

## 2.0 Why we need soft proofing for 3D printing

To demonstrate the utility of a soft-proofing solution an illustrative example will be used. *Fig. 1a* shows a screenshot of a 3D design software where a designer created a simple part that will later be printed on a 3D printer. In contrast*, Fig. 2* shows the actual part that was printed. The perceptual differences between the designed part and the printed part are clearly visible, mainly coming from technology limitations of the 3D printer: First, the colors on the designed part (digital version in *Fig. 1*) look brighter and more saturated than the colors of the printed part (*Fig. 2*). Second, the printed part has a rough appearance that is not shown in the modelling software. Third, some patches of the printed part seem to be non-uniform in appearance. This mottling is a result of the printing process and is not represented by the CAD software. Other differences that exist but are not shown in *Fig. 1* include that the colors of the printed part depend on the orientation of the part. For instance, the same color printed on both top and bottom of the part may appear differently. Furthermore, specular reflections that might be present in the printed and postprocessed part are not represented in the initial visualization.

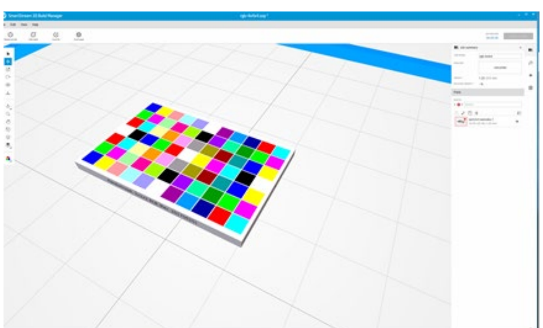

*Figure 1. Original computer designed part shown on the monitor.*

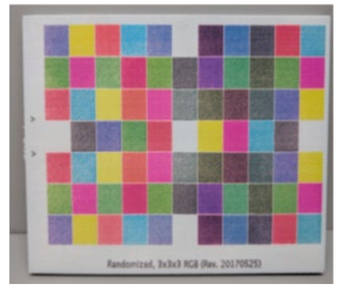


*Figure 2. Photograph of the corresponding 3D printed part.*

## 3.0 HP SmartStream 3D Builder – a current soft-proofing solution

We propose a method for any 3D design software to consider the particularities of the 3D printer that will be used to print the part and use that information to generate a soft-proof of the printed part. Specifically, the 3D printer capabilities (like color gamut, printing material, print mode, layer thickness or any other printing parameters that may affect the appearance of the printed part) are communicated through an API to desktop applications used to design 3D objects. Hence, the desktop application performs the following steps:

1) Loads a 3D model in any available format (e.g. STL, OBJ,3MF)
2) Retrieves information from the printer regarding all printer capabilities that affect the appearance of the part, including print mode, material, available color agents, layer thickness, and information of the appearance of printed colors (e.g. through one more ICC profiles)
3) Generates an accurate soft-proof of the part using a rendering algorithm. This includes
    a. The visualization of the 3D object under a D50 illumination
    b. Accurate visualization of the diffuse color component using ICC profiles specific to the actual printer, materials and print mode chosen by the user. Here the conscious decision was made for the print preview to use simple ambient illumination for the rendering to avoid any confusion about color modifications due to the shape of an object and/or the direction of the light source. While not photorealistic, this approach isolates the color aspects of the surface and limits the influence of other surface effects. Including more complex surface effects in future implementations is discussed in section 4 of the paper.
    c. If the visualized printed color of an object doesn't correspond with the desired color a user can either change the material and/or print mode and determine if that makes a difference in terms of color, or they can modify the original color of an object by modifying the hue, lightness and saturation component and rechecking the effect on the printed color.
    d. The print preview of the object itself is augmented with the RGB view and print view

of 2D color patches. In that way the user can select any RGB color and quickly obtain a print preview.

The color characteristic of the printing system (printer, materials, agents and print mode) is obtained by measuring a discrete set of color samples with a commonly used spectrophotometer and creating an ICC profile.

*Fig. 3* depicts the print preview of the 3D model shown in *Fig. 1* generated by the current version of the HP SmartStream 3D Builder. It is a rendering of the printed object and can be compared to the photograph of the 3D object depicted in *Fig.2*. The user can see the color changes that will happen during printing. Further improvements to make the renderings more photorealistic can and will be made. They are discussed in section 4 of this paper.

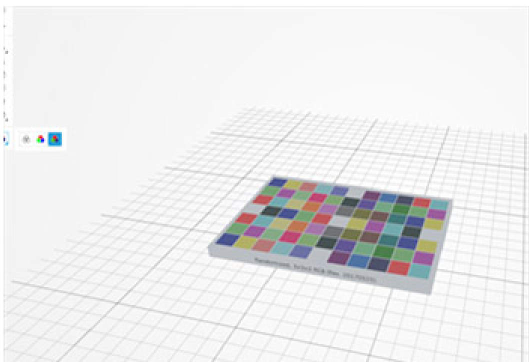

*Figure 3. Print preview of 3D model depicted in Fig.1.*

### 3.1 An Appearance Reference Object

To demonstrate the utility of a soft-proofing solution we refer to an illustrative example in the field of 2D large format printers: "test prints" are often used to showcase the color capabilities of the printing system and can typically be initiated with the push of a button on the printer's menu. A similar approach is required for 3D printers. Designers specify the colors of 3D objects in the sRGB color space, but they don't have any information of how those colors will look once they are printed. Furthermore, many of the current 3D printing technologies exhibit color variations dependent on the surface normals of an object and how the part has been positioned within the print bed. Some companies (e.g. Stratasys or Cipres) partially address the issue by providing a small set of flat printed example objects.

For our soft-proofing system, we specifically designed an *Appearance Reference Object (ARO)*, which consists of 3D sub-objects (*Fig. 4c*), that showcases the color capabilities of the printing system, is scalable, and demonstrates the color of several different surface normals (*Fig. 4*). It has flat planes for the top, bottom, side, and 45-degree faces of the object, as well as curved surfaces in between, providing a detailed sense of the role of orientation on color. As each element is labeled with the sRGB values on the back (*Fig. 4b*), a designer can use those elements as a color reference like Pantone color chips.


*Figure 4a. Front of the Appearance Reference Object.*


*Figure 4b. Back of a portion of the Appearance Reference Object.*

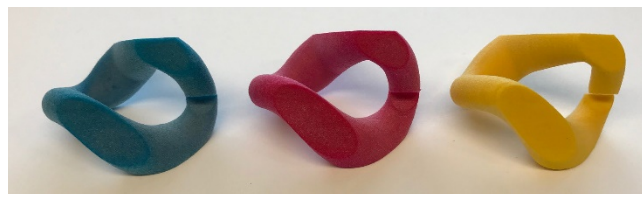

*Figure 4c. Separated Elements of the Appearance Reference Object.*

The Appearance Reference Object is integrated into the soft proofing system and appears with the click of one button. A soft-proofing can be performed on the monitor and the object can also easily be printed. A designer can also customize the object by either modifying the colors of individual elements or by simply defining a color palette and then having the software automatically create an appearance reference object with the customized colors. They can 3D print their customized appearance reference object, and subsequently use the printed part to complement the soft-proof they see in HP SmartStream 3D Builder.

As shown in *Fig. 4a*, the elements are supposed to be printed interlinked, but can be disassembled (Fig. 4c) and reassembled. They also have surfaces that are big enough for color measurements if desired. A video summarizing the color capabilities of the HP SmartStream 3D Builder is available at [19].

## 4.0 Envisioned future expansions

The current implementation is the first step towards a holistic soft-proofing system. Moving forward we want to integrate continued development in 3D printing technologies, materials, and post-processing, with existing computer graphics techniques into future expansions.

Our system currently only visualizes the single appearance attribute of diffuse color for the print preview. The glossiness of a surface may also vary by using different materials or one of many post-processing applications. In soft-proofing terms this simply means using spot light sources and accounting for specular reflections. Different materials, printing modes and post-processing applications (e.g. sand blasting, tumbling, dying, waxing) might result in different degrees of roughness that is inherent to the material. Rendering that roughness of the material in the soft-proof is also desirable. In an ideal case, roughness should become more apparent as a user zooms in to an object. Currently, designers can easily use 2D texture maps to obtain spatial varying colors. Eventually, it will become common practice to use 3D textures for 3D printed objects. They could be defined mathematically or obtained through a material scanning device and made available like color palettes. Users would then simply apply them to 3D objects. Corresponding displacement maps can be used for the preview.

Improvements in rendering color can also be made. A single color applied to a 3D object doesn't result in one single printed color. In fact, what we get is a spatially varying color. Spectrophotometers currently used to characterize the color characteristics of a printing system average over a small area and provide a single uniform color measurement. Sophisticated material appearance capturing systems like the TAC7 from X-Rite [15] are available and can be used to capture appearance attributes like gloss, roughness, color and their spatial variations. Details about capturing, artificially modifying and using material characteristics of 3D printed samples for visualizations of printed objects are discussed in a previous paper [16].

Another desirable feature of a future soft proofing application would be the ability to see an object in a variety of realistic environments. Those would obviously be application specific. For this function we could take advantage of the commonly used Computer Graphics technique of environment maps.

### 4.1 Conveying appearance meta information

Visualizing the expected appearance of a 3D printed object is a start, but other aspects of a 3D printed part could also be provided as meta information. This feature is inspired by Adobe Photoshop's functionality of showing which colors of an image will be outside the color gamut of a printing device. In the case of 3D printing for expected printed appearances those could be the following features:

1) Incorporate general functionality to easily convey appearance differences resulting from material changes, print mode changes, or applying post processing.
2) Highlight colors in an object where the user should expect to see strong changes from the colors on a monitor to the colors of the printed objects.
3) Highlight colors in an object where the user should expect that the naming boundaries are crossed (A user would use a different name to verbally describe the color of an object on the screen versus the printed object).

### 4.2 Conveying a basic set of mechanical information

Meta-graphic information could extend beyond just appearance properties. Displaying an infographic view of mechanical properties that for example shows the difference in strength between printing with two different materials would be useful. These views can be color-coded by thresholds. The mechanical properties within a part could also be visualized, for instance weak points in a part could be identified.

## 5.0 Conclusions

The data that we are providing through an API of HP's 3D color printer to desktop 3D design applications are holistic and will enable those applications to provide soft-proofs that are both communicating the appearance attributes (color, glossiness, texture) as well as basic mechanical information of 3D parts. Those applications can also provide meta information comparing the effect of printing materials, printing modes and post processing applications on the expected appearance of 3D printed parts. In addition, the system also makes "Appearance Reference objects" available to effectively showcase expected appearances both on the monitor and in physical form.

As of today, we are not aware of another 3D printing system that has all these capabilities. Adobe has defined a 3D Printer Description File Format [17], which lets 3D printer companies define 3D printer profile files. Those files contain lots of information necessary to actually print 3D objects mainly through extruder type 3D printers. They also contain information describing the appearance of the material. However, the material is just mono-color assuming that the printer can only print objects using one color at a time. The 3D printer manufacturer is expected to provide the information to Adobe, which is only one software package out of many a designer may use.

In our case we are envisioning to provide information about a full color printer. Furthermore, we are providing the information once and the burden is on the 3D design applications to get the information from the printer itself.

In addition to the work descried here, ISO/TC130/JWC 7 (ICC WG: Colour Management) is working on a new ICC standard [18], which will enable new ICC profiles to not only contain information about diffuse color, but also about material properties (e.g. BRDF, height information). That information can then be used for visualization purposes. Hence, the information about the appearance of 3D printed object using a variety of different materials, printing modes and potentially postprocessing applications, could be stored in those new ICC profiles and then used for rendering purposes. Again, those profiles would be provided by the 3D printers and the design applications would pull the information from our 3D printers and use them. In the implementation mentioned above we are only using commonly used ICC profiles, but this can be expanded as our soft-proofing method continues to evolve.

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## Authors Biographies

*Ingeborg Tastl received her MS in Computer Science from the Technical University in Vienna, Austria (1990) and her PhD in Color Science from the Technical University in Vienna, Austria (1995). After her PostDoc at ENST in Paris, France, she worked for Sony's Research Lab in San Jose, California (1998-2001). Since 2001 she has worked for HP Inc. Laboratories in Palo Alto, California. Her current research focus is on the appearance capture and reproduction of 3D objects. She has been an active member of IS&T.*

*Miguel A. Lopez-Alvarez received his M.Sc. in Advanced Physics in 2006, and his M.Sc. in Electrical Engineering and Ph.D. in Color Science in 2007 from the University of Granada (Spain), where he served as an Assistant Professor in optics and photonics. Since 2008, has worked as a color imaging engineer for HP Inc., focusing on color pipeline architecture, color sensors and color calibration of printers, scanners and cameras. Dr. Lopez-Alvarez has been and Associate Editor for the IS&T Journal of Imaging Science and Technology from 2013 until 2016.*

*Alex Ju received her BFA in jewelry and metalsmithing from the Rhode Island School of Design (2016). Since then she has worked as a research engineer at HP Inc. Laboratories in Palo Alto, CA. Her research work spans several facets of 3D printing, including applications, experiences, post-processing, and education.*

*Morgan Schramm holds a BS in Electrical and Computer Engineering from UC Santa Barbara (1991) and an MS in Computer Science from the University of Oregon (1995), where he also served as an instructor. He worked on Analog CAD systems for National Semiconductor in Sunnyvale, California (1991-1993). Since 1995 he has been with HP Inc. in Vancouver Washington, where he has focused on color ink-jet printing, consumer photography, and 3D color printing.*

*Jordi Roca received his BS in Mathematics from the University of Barcelona (2006), an MS in Mathematical Engineering from the Polytechnic University of Catalonia (2009) and his PhD in Computer Science from the Autonomous University of Barcelona (2012). He worked as a research engineer in Computer Vision focused on industrial 3D quality inspection. Since 2015 he has been with HP Inc. in San Cugat (Barcelona, Spain) working on 3D printing.*

*Matt Shepherd received his BS in Mechanical Engineering (summa cum laude) from the University of Washington (1994). Since 1995, he has worked for HP Inc. in Vancouver, Washington in 2D and 3D printing.*

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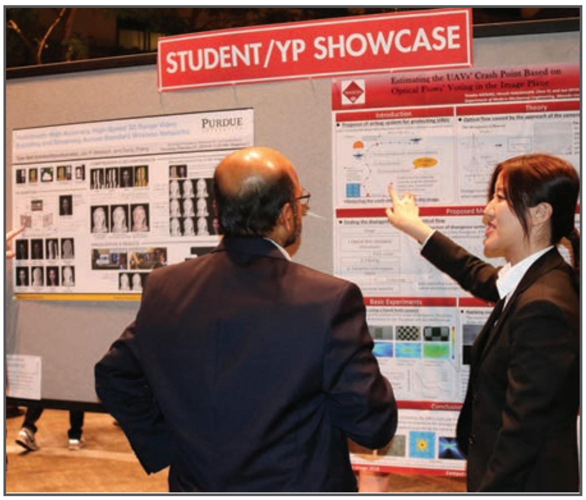


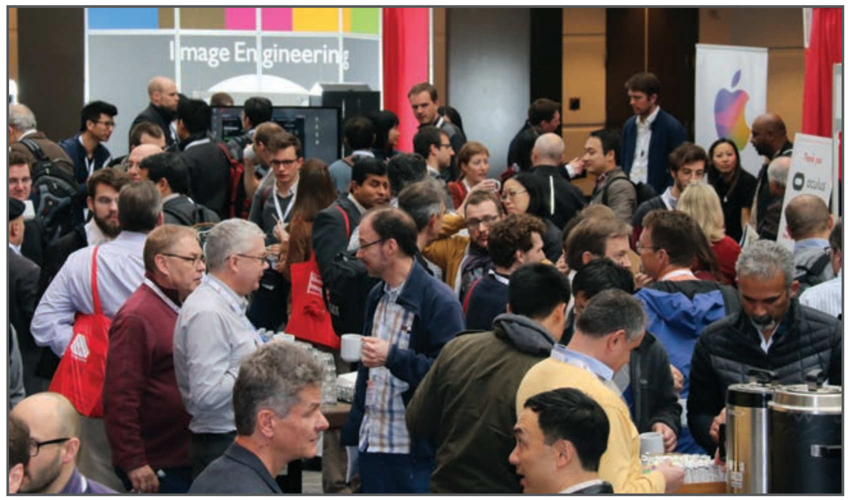



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