Challenges for 3D High-Fidelity Soft Proofing

John Recker, Ingeborg Tastl, Eric Hoarau, Udi Chatow; Printing and Content Delivery Lab, HP Laboratories, Palo Alto, CA

Abstract

This paper contends that current soft-proofing systems for print products should more correctly be described as soft-preview systems. They currently do not visualize the appearance and mechanical properties of a final printed and finished product with sufficient accuracy to be part of a formal enforceable contract between manufacturer and buyer. This paper discusses a systematic approach to assemble a measurement-based system which measures, models, renders and evaluates visual appearance attributes like gloss and elaborates on existing approaches and challenges that must be addressed in order to implement a high-fidelity real-world soft proofing service for a scalable web-to-print application.

Introduction

Manufacturing today is dominated by commoditization of mass produced goods enabling a worldwide internet marketplace backed by enormous economies of scale. And yet the next generation of manufacturing technologies is already appearing on the horizon: personalized manufacturing where items are customized to a user's exact specification and built to order. Central to a build–to-order system is a sophisticated front end giving users the ability to compare, contrast and select from a wide range of design choices while nonetheless limiting the end result to a manufacturable and functional final product. This system does not only have to simulate the functional aspect of the product under design, but also to generate a predictive rendering of the item; reproducing the "look and feel" of the design such that a consumer is confident making a purchase and is satisfied with the final delivered product.

The Graphic Arts Industry has used hard-copy proofs of to-be-printed products for a long time as part of the contract between a Print Service Provider and a Print Buyer. However with the shift from analog to digital presses enabling the efficient production of short run jobs and with the increased submission of jobs through the web hard-copy proofs, which delay production and require extra resources, have become impractical. Software companies have responded to this challenge by building a number of different systems for visualizing manufactured print products. It is our contention, however, that these software packages are, for the most part, previews as opposed to proofing systems.

A hard-copy proof is generally a part of the contract between a print buyer and a provider. A buyer expects that the final printed product will, perhaps within some manufacturing tolerances, closely resemble the proof. Failure to deliver a product that meets these criteria can be seen by the buyer as a failure to meet the terms of the agreed-upon contract, perhaps resulting in the print product having to be re-printed at the PSP's expense.

The soft-proofing systems available today fail by-in-large to meet this stringent standard of visual quality. What's needed for web-to-print applications in specific and web-based storefronts for on-demand manufacturers in general is an enhanced digital version of the old contract proof. It must visually communicate the static and dynamic appearance and the relevant mechanical properties of the finished product. The resulting simulation should be driven by measurements of the physical characteristics and the manufacturing tolerances of each of the components of the final product, by analysis of the display technologies on which the simulation are displayed, and by an understanding of the human appearance perception models. Furthermore, the tools and procedures required for each of these steps have to support large scale solutions and their use cannot be limited to expert users alone.

While we ultimately believe that a soft proofing system must simulate both the mechanical and visual properties of a print product, our efforts to date have focused on the visual appearance properties of print products, and we will not further discuss the simulation of mechanical properties of print products.

The following sections discuss a framework for a measurement based soft proofing system that consists of four distinct elements, Measurement, Modeling, Rendering and Evaluation that are applied for each one of the visual appearance attributes gloss, color, translucency and texture as defined by the CIE. The state-of the art approaches and challenges to characterize and visualize gloss appearance are discussed in more detail as an essential part of a high quality, scalable service for a web-to-print application

Framework for a soft-proofing system

We have found the visual appearance framework from the CIE technical committee 1-65 [1] (Figure 1) a convenient and comprehensive framework for organizing our work.

This framework divides the characterization of the visual appearance of materials into four categories: *Color*, *Gloss*, *Translucency*, and *Texture*. This schema has the advantage that it generally matches the analysis of visual appearance in both the vision and graphics communities as well as in the Graphic Arts industry.

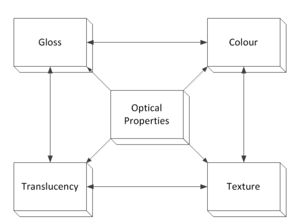

***Figure 1**: Visual Appearance framework from CIE committee 1-65 [1]*

We furthermore separate the characterization of each of these visual appearance components into four steps: *Measurement, Modeling, Rendering and Evaluation*, with the understanding that solutions obtained for each step must be appropriate to the expected user base of a soft proofing system including Print

Service Providers, and expert and non-expert buyers and must ultimately support commerce at internet scale.

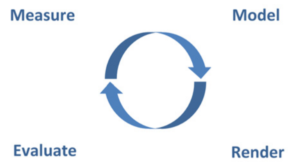

***Figure 2**: Four steps for integrating a visual appearance characterization into a proofing system.*

Measurement, in this instance, refers to sampling the physical manifestation of the visual appearance with measurement tools. For example, the color of a reflecting material might be measured with a spectrophotometer. The gloss of a material might be sampled with a gloss or haze meter, or more completely with a gonio-spectrophotometer.

Ideally, the sampling of the material of interest would capture sufficient detail and accuracy to allow direct use of the data for predicting the appearance of the material for a simulation in a variety of environments. In practice, however, this is rarely the case. Instead, parameters of a mathematical model of the appearance characteristics under observation must be fit to the collected data. For example, the computer graphics community has developed a number of material reflection models including empirical models such as the Ward [2] model and more physically based models such as the Cook-Torrance [3] model to simulate material reflection for rendering systems. Fitting captured measurement data to these models allows both interpolating missing data and, in some cases, significantly reduces the quantity of data needed for prediction and simulation of material behavior from measurement data.

Rendering is a key component of a soft-proofing system. In this case, rendering refers to creating a simulated view of the print product under consideration. This view might be a static view, or a dynamic view that allows interactive manipulation of the various components of the print product. For example, the proofing system might simulation the bending of a stiff material intended for a marketing brochure. However, as will be further explained later in this paper, the rendering system must consider both the print product under consideration and the environment in which the print product is to be evaluated.

Evaluation of the simulated result is the last important step. One important consideration, as noted, for example, by Sève [4]:

> *"... it is customary to consider three aspects in the field of appearance: physical, physiological, and psychological. ... For instance, and following mainly Bartleson's idea [5], gloss and associated appearance aspects, such as haze, depend on the geometrical spatial distribution of light reflected by the objects (physical aspect); then this light distribution stimulates the human visual system, for which it is advisable to consider binocular vision (physiological aspect); and finally, thanks to long training, these stimuli are interpreted by the cortex and recognized as objects and as peculiar features of these objects (psychological aspect)."*

Critically, it must be noted that current display technologies will prevent us from a achieving a perfect simulation of the light reflected from a print product and reaching the visual system of an observer. Displays are limited by their color gamut, dynamic range and multiview capabilities such that they are inherently unable to generate a light field indistinguishable from the light field reflected from a manufactured product. Given these display limitations, it is our beliefs that the perception of material appearance that must ultimately drive the quality criteria developed for a soft proofing system, and that only techniques that are validated by the results of psycho-physical experiments will ultimately achieve a system that meets the quality standards necessary for a true soft proofing system.

The *Measurement, Modeling, Rendering and Evaluation* framework can be applied to each of the visual appearance characteristics from the CIE visual appearance framework. In the next sections, we will examine how this framework can be applied to the analysis one of the CIE visual appearance components gloss.

A brief overview of gloss

Gloss, according to [1], is associated with the manner in which light is reflected from a material near, or at, the specular direction. Gloss is typically perceived independent of the color of the material itself, though some materials – metals in particular - influence the color of the specular reflection more strongly than others. Hunter [5] proposed that five types of gloss can be perceived including specular gloss (Figure 3).

Though gloss clearly is strongly influenced by the physical properties of a material and its interaction with light, according to the CIE, gloss is "the mode of appearance by which reflected highlights of objects are perceived as superimposed on the surface

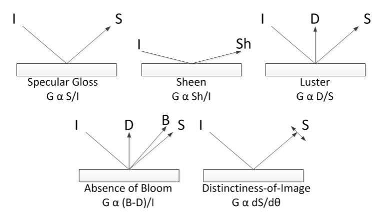

***Figure 3**: Hunter's five types of gloss (from [1])*

due to the directionally selective properties of that surface" [7], and this ultimately is a psycho-physical phenomena.

Substantial effort has been dedicated to understanding the psycho-physical nature of gloss perception. Hunter and Judd [8] noted a non-linear relationship between gloss perception and specular gloss (Figure 4a). Harrison & Poulter [9] demonstrated a relationship between gloss perception and surface luminance and noted that specular gloss was, by itself, insufficient for ranking samples of different gloss levels (Figure 4b). Aida [10] describes that the visual glossiness of colored paper depends primarily on the surface luminance. Kuo [11] measured just-noticeable-differences (JND) for specular gloss of materials illuminated by an 60^o illuminant. Ferwerda and Pellacini [12] identified two dimensions of gloss from psycho-physical experiments using rendered images of spheres which resemble Hunter's specular gloss and distinctness-of image. Obein [13] observed that "gloss scaling seems to be independent of the geometrical variations of the luminous flux at the surface of the sample", a property described as "gloss constancy". He further observed a higher sensitivity to gloss differences for binocular vision than for monocular vision. Blake and Bülthoff [14] further demonstrate a clear relationship between gloss perception and binocularity and "conclude that human visual analysis seems to employ a physical model of the interaction of light with curved surfaces, a model firmly based on ray optics and differential geometry". Nishida and Shinya [15] demonstrate that gloss matching can only be accurately achieved for similar shapes. Vangorp [24] demonstrates that objects with moderate surface undulations provide more stable perceptions of gloss than simple objects like spheres. Fleming [16] "demonstrates that subjects can match surface reflectance properties reliably and accurately in the absence of context, as long as the illumination is realistic. These findings suggest that subjects do use stored assumptions about the statistics of real-world illumination to estimate surface reflectance". Phillips and Ferwerda [17] demonstrate that "limiting image dynamic range does change the apparent gloss of surfaces depicted in the images".

Together these studies indicate that great care must be taken when designing a proofing system for presenting a simulation of a glossy material. Of particular importance, for a user to form an accurate impression of the glossiness of a print product, is that the simulation must not only reproduce the reflectance properties of the material, but also the shape of the material. Furthermore, the interaction of the light field incident on the simulated object from the environment in which the print product is to be evaluated has to be properly modeled.

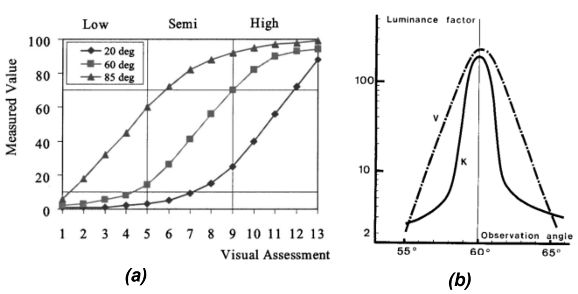

Figure 3: (a) Visual gloss vs measured gloss for different incident light angles, (b) Gloss lobes of two materials with similar specular gloss peaks but differing lobe width (both from [4])

The soft-proofing framework and gloss

A variety of devices are available for measuring the gloss of a material - from gloss meters, to haze meters to multi-angle measurement devices to gonio-spectrophotometers and different solutions using image sensing devices like cameras and scanners. The challenge, from a proofing perspective, is selecting a device that enables both capturing sufficient detail of the reflection characteristics of a material and that has a price point that allows wide-spread adoption of these devices – at the least by PSPs and professional buyers. Gloss meters are not sufficient for the task, as can be seen in Figure 4(b). Materials can, for example, be found with similar specular gloss but differing gloss lobe width and gonio-spectrophotometers are currently prohibitively expensive for widespread adoption. Another approach suggested by Ren et al. [19] uses a camera based systems for capturing surface reflectance. While this approaches show promise, key psychometric measures are missing to validate this approach. For example, while Kuo [11] proposes a metric for JND of specular gloss of materials illuminated by a 60^{o} illuminant, the authors note that the thresholds will change when other visual gloss attributes beyond specular gloss are included. The study further notes that there isn't an established viewing condition to study gloss as the *Standard Observers Viewing* condition when examining color. Missing, therefore, are more comprehensive metrics, which establish the relative importance of the standard appearance metrics, the JND visual thresholds for each of the metrics, and the conditions under which the various appearance metrics should be used.

Modeling of glossy materials is similarly constrained by this lack of perceptual metrics for gloss perception. Ferwerda [12] develops a psychophysically-based model of surface gloss, with dimensions that are both physically and perceptually meaningful and provides scales that reflect our sensitivity to gloss variations. However the axes do not correspond to directly measurable physical quantities. Westlund and Meyer [18] propose a system for directly mapping ASTM standard appearance measures to computer graphics rendering models by numerical integration of rendering models. A challenge for using this approach for mapping appearance measures to rendering model parameters is that there are more appearance measures than degrees of freedom in common rendering models, and a lack of standards for prioritizing one measure over another. Recently, Forés Herranz [20] proposed a perceptually based error metric to be used for fitting rendering model parameters to gonio-spectrophotometer measurement data to improve the visual fidelity. Missing, however, is a direct comparison to a real-world scenario, with an actual physical object and a specific viewing environment.

Previous research has shown that the visual appearance of a material is a function of both the material and the environment in which the material is examined. A proofing system must therefore not only correctly simulate the reflection of incident light from a material of interest, but properly simulate the environment in which the material is to be evaluated. While the color community has developed standard illuminants and light booths to standardize viewing conditions for color evaluation, no similar standards exists for gloss. Fleming [16] has shown that the light incident on a glossy surface must exhibit real-world statistics for proper gloss perception – thus it is likely that a light booth is not the proper viewing condition in which to form a correct impression of the gloss of a material. In addition, gloss is typically best appreciated by moving a glossy object under a light source, so it is likely that a system for proofing gloss will have to be an interactive system allowing real-time or at least near-real time manipulation of the object in the virtual environment. Building a real-time rendering system that renders a perceptually accurate scene has been one of the grand challenges in computer graphics. Research has been conducted in measuring the perceptual impact of light transport simplifications for achieving real time performance. For example, leveraging the work of Ramanarayanan [21] on "visual equivalence", Křivánek [22] performed a set of psycho-physical experiments resulting in simple heuristics to guide visually equivalent and efficient rendering, and in a method for correcting energy losses in VPL renderings. This work provides a strong perceptual foundation for a popular and efficient class of global illumination algorithms.

Another significant issue for soft-proofing systems is the limitations of current display technologies. Phillips [17] observes that that objects shown in SDR images are perceived to have lower gloss than objects shown in HDR images; and that gloss differences are less discriminable in SDR images than in HDR images. It is possible better tone mapping operators might help: Ledda [23] reports that in psycho-physical studies tone mapping operators seems to trade off contrast sensitivity with color accuracy. Missing, however, are studies which match real world scenes against rendered scenes.

Ultimately, perceptual metrics must be developed that enable quantitative evaluations of comparisons of materials rendered in virtual scenes with corresponding real materials in similar environments.

Conclusion

In conclusion we have discussed the motivation for offering a high fidelity soft proofing solution for web-to-print applications, which is time and money. We have also highlighted the fact that soft proofs can only serve as substitutes for hardcopy contract proofs if they can accurately communicate the static and dynamic appearance and mechanical properties including manufacturing tolerances. In order to achieve that the visualizations need to be measurement based. This holds true not only for color, but also for gloss, translucency and texture as well as for mechanical properties. Within this paper we have as an example focused on the gloss attribute, discussed the four steps of a systematic approach: Measurement, Modeling, Rendering and Evaluation and provided an overview of existing approaches and challenges to make a high quality soft proofing solution that is scalable and suitable for real-world web-to-print implementations a reality.

References

[1] CIE Technical Committee 1-65 of Division 1, A Framework for the Measurement of Visual Appearance, CIE175:2006 (2006).

[2] Gregory J. Ward, Measuring and Modeling Anisotropic Reflection, Proceedings of the 19th annual conference on Computer Graphics and Interactive Techniques (SIGGRAPH 1992), pg. 265 (1992).

[3] Robert L. Cook and Kenneth E. Torrance, Reflectance Model for Computer Graphics, Proc. 8th conf. on Computer Graphics and Interactive Techniques, Vol. 15, No. 3 pg. 301 (1981).

[4] Robert Sève , Problems connected with the concept of gloss , Color Research & Application, Volume 18, Issue 4, pg. 241 (1993).

[5] C. J. Bartleson, Gloss measurements, Report to the CIE TC 2-3, 1974.

[6] R.S. Hunter, The Measurement of Appearance, Wiley, New York (1987).

[7] Commission Internationale de l'Eclairage, CIE International lighting vocabulary (4th ed.) (Publication CIE 17.4 - 1987). Paris: Bureau central de la CIE (1987).

[8] R. S. Hunter and D. B. Judd, Development of a method of classifying paints, ASTM Bulletin 97, pg. 11 (1939).

[9] V. G. W. Harrison, S. R. C. Poulter , Gloss measurement of papers - the effect of luminance factor , Br. J. Appl. Phys. Vol. 2, 4 pg. 92 (1951).

[10] Teizo Aida, Glossiness of Colored Papers and Its Application to Specular Glossiness Measuring Instruments, Systems and Computers in Japan, Vol. 28, No.1 pg. 95 (1997).

[11] Chunghui Kuo, Yee Ng, and Jeffrey C. Wang, Differential Gloss Visual Threshold Under Normal Viewing Conditions, NIP18: International Conference on Digital Printing Technologies, San Diego, California; pg. 467 (2002)

[12] Ferwerda, J. A., Pellacini, F., & Greenberg, D. P., A psychophysically-based model of surface gloss perception, Proceedings of SPIE, 4299, pg. 291 (2001).

[13] Gaël Obein, Kenneth Knoblauch, Françoise Viénot, Difference scaling of gloss: Nonlinearity, binocularity, and constancy, Journal of Vision August 30, 2004 vol. 4 no. 9 article 4 pg. 711 (2004).

[14] Andrew Blake, Heinrich Bülthoff, Does the brain know the physics of specular reflection?, Nature, Vol. 343, No. 6254 pg. 165 (1990).

[15] Shin'ya Nishida, Mikio Shinya, Use of image-based information in judgments of surface-reflectance properties, JOSA A, Vol. 15, Issue 12, pg. 2951 (1998).

[16] Roland W. Fleming, Ron O. Dror, Edward H. Adelson, Real-world illumination and the perception of surface reflectance properties, Journal of Vision 3, pg. 347 (2003).

[17] Jonathan B. Phillips, James A. Ferwerda, Stefan Luka, Effects of Image Dynamic Range on Apparent Surface Gloss, Proceedings IS&T 17th Color Imaging Conference, pg. 193-197 (2009).

[18] Harold B. Westlund, Gary W. Meyer, Applying Appearance Standards to Light Reflection Models, Computer Graphics, Annual Conference Series. ACM SIGGRAPH 2001. pg. 501 (2001).

[19] Peiran Ren, Jiaping Wang, John Snyder, Xin Tong, Baining Guo: Pocket Reflectometry, ACM SIGGRAPH (2003).

[20] Adria Forés Herranz, James Ferwerda, Jinwei Gu, Toward a Perceptually Based Metric for BRDF Modeling, submitted to IS&T/SID Color Imaging Conference 2012.

[21] Ganesh Ramanarayanan, James Ferwerda, Bruce Walter, Kavita Bala, Visual Equivalence: Towards a New Standard for Image Fidelity, ACM SIGGRAPH 2007 papers, ACM, New York, NY, USA (2007)

[22] Jaroslav Křivánek, James A. Ferwerd, Kavita Bala, Effects of Global Illumination Approximations on Material Appearance, ACM SIGGRAPH 2010 papers, ACM, New York, NY, USA (2010)

[23] Patrick Ledda, Alan Chalmers, Tom Troscianko, Helge Seetzen, Evaluation of Tone Mapping Operators using a High Dynamic Range Display, Journal of Vision vol. 4 no. 9 article 4, pg. 711 (2004)

[24] Peter Vangorp, Jurgen Laurijssen, Philip Dutre´, The influence of shape on the perception of material reflectance, ACM Trans. Graph. 26, 3, pg. 1 (2007)

Author Biography

John Recker is a researcher with the Print and Content Delivery Laboratory at Hewlett-Packard Laboratories in Palo Alto, CA. John received a BSEE from Cornell University. He has specialized in building graphics systems for windows systems, CAD and gaming for both commercial and research applications, and is now focused on bringing these technologies to digital production for commercial print.

Ingeborg Tastl received her MS in computer science from the Technical University in Vienna, Austria (1990) and her PhD in computer science / color science from the same university in 1995. After a PostDoc at ENST in Paris, France, she worked for Sony's US Research Lab in San Jose, California in the area of color pipelines for digital still cameras (1998-2001). Since 2001 she has worked as a color scientist at HP-Labs, Palo Alto, CA. Her work has focused on color and imaging issues in the area of consumer, commercial and industrial printing applications. She is representing HP at the ICC, has been a Technical and General Chair of the IS&T Color Imaging Conference and is currently a Board Member of IS&T.

Eric Hoarau is a senior researcher with Hewlett-Packard Laboratories (Palo Alto, California). He received his B.S. from the University of California at Berkeley and his M.S. in Mechanical Engineering from the Massachusetts Institute of Technology. His research interests span several fields: Mechatronic systems, imaging systems, color imaging algorithms, distributed computing and system dynamics.

Udi Chatow received his B.Sc. and M.Sc. degree in Physics from Tel Aviv University and his MBA from Kellogg / TAU. Udi joined HP-Indigo in 1988 and has held several R&D positions among them Project Manager, Ink Department Manager, and R&D Materials Section Manager and since 2005 is creating and leading incubations in HP Labs.