EUROGRAPHICS Workshop on Graphics and Cultural Heritage (2018)
R. Sablatnig and M. Wimmer (Editors)

Short Paper

Gloss Calibration and Gloss Gamut Mapping for Material Appearance Reproduction of Paintings

W.S. Elkhuizen [1], T.T.W. Essers [1], Y. Song [1], S.C. Pont [1], J.M.P. Geraedts [1] and J. Dik [2]

[1] TU Delft, Industrial Design Engineering, The Netherlands, [2] TU Delft, Mechanical, Maritime and Materials Engineering, The Netherlands

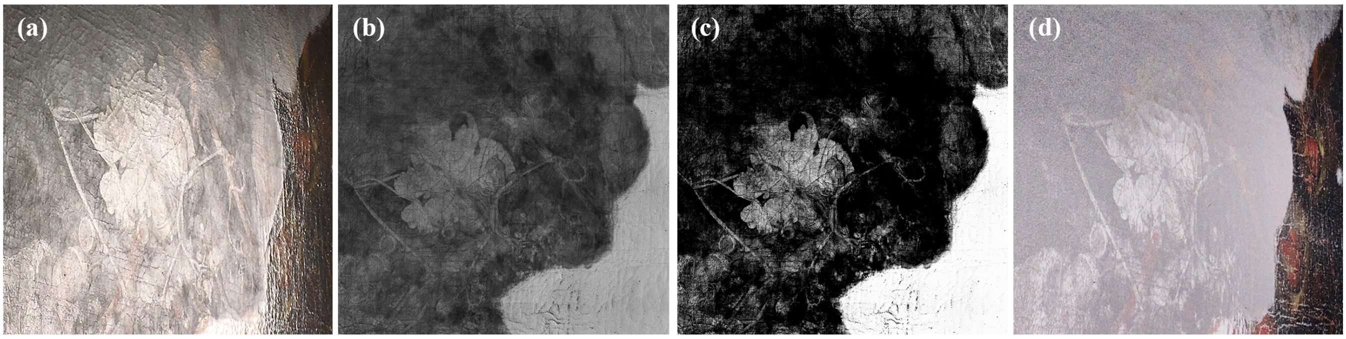


Figure 1: *Detail of reproduced painting, which was undergoing restoration, with varnish layer(s) still present in bottom right corner, showing (a) the painting, (b) gloss scanning result, (c) gloss values mapped to printable gloss, and (d) the 3D printed result including color, relief and gloss variations. Figure (a) and (d) are photographed under similar illumination and viewing angles to show the reflection of the surface.*

Abstract

Being able to link captured material characteristics and fabricable material appearance attributes is important for creating life-like reproductions. In this paper we propose a method for gloss calibration, and an approach for gloss gamut mapping, as part of an integrated approach for color, topography and gloss reproduction. For gloss calibration, gloss calibration targets were printed in the primary printing colors (CMYK and White), with uniform gloss in equal distant gloss levels. These targets were scanned using the proposed gloss scanner. To create the gloss gamut map, a monotonic curve was fitted to the mean gloss scan values at different gloss levels. Analysis of fitted curves indicated that the gloss mapping is independent of the diffuse colors. As a case study, the painting 'Fruit Still Life' by Cornelis de Heem was scanned, and the measured gloss was mapped to printable gloss levels using the relation described by the fitted curve. The printed result shows good correspondence to the painting's appearance, with clearly distinguishable gloss features for the in-gamut glass values.

CCS Concepts

•Computing methodologies** → **Reflectance modeling;** **•Applied computing** → **Fine arts;

1. Introduction

The appearance of a painting is determined by various characteristics of the surface of the painting. A poster showing the depiction presented in a painting will not easily be mistaken for the original painting. One of the reasons for this is that a poster is a flat color print and lacks the subtle height variations of a painting's surface as well as variations in gloss and translucency of the paint layers [EZV*14]. If these aspects can be captured and replicated, a more life-like reproduction might be created. Reproducing the appearance of objects and materials is not new. Artifacts have been (partly) copied since ancient times. In most cases, artifacts and material appearance reproductions are either handmade by highly skilled craftsmen or mass-produced, where a limited set of appearances is fabricated. Advances in computer graphics have made it possible to accurately capture and digitally render material appearance. Meanwhile, the development of multi-material 3D printing in the past decades also made it possible to reproduce the captured information physically. For this, a connection needs to be made between the captured information and the fabrication of appearance. However, extensive literature study did not reveal any

DOI: 10.2312/gch.20181354

methods for gloss calibration and gamut mapping (independent of diffuse color mapping). Building on previous research [EEL*17], this paper presents a method for calibrating the captured information for gloss reproduction.

2. Related work

(2D) color reproduction is already largely standardized using color calibration targets, and procedures where input and output devices can be connected through a device independent 'Profile Connection Space' [Int10]. In most cases where a printing system has a more limited color space than the imaging device, gamut mapping needs to be applied where, according to a rendering intent, the input colors are mapped to the range of possible printable colors [Ber00]. However, a (standardized) calibration and gamut mapping approach for gloss does not exist (yet). Glossmeters are often used instruments in the printing industry, to take spot measurements of specular reflection gloss of a surface [Int14]. Glossmeters use a polished, black glass plate as a standard reference, and gloss is expressed in Gloss Units (GU), which provide a relative measurement to the reference [Int14]. Although these can be used to verify gloss uniformity, their applications in capturing spatially varying gloss are limited due to the data capturing speed and the need for surface contact. Various methods have been developed to capture spatially-varying reflectance for globally flat surfaces (e.g. [PSM02, GTHD03, RWS*11, AWL13]). Most have been developed for the purpose of computer rendering. Therefore the gloss levels and the printable color spectrum are not associated. Several approaches have been proposed for the fabrication of spatially-varying reflectance. Matusik et al. [MAG*09] fabricated isotropic material appearances (2D printing) using a linear combination of multiple printer inks. A distance metric, based on rendered spheres of the BRDFs, was used to map the target BRDFs (input) to the print BRDFs. Lan et al. [LDPT13] were able to fabricate anisotropic BRDFs by combining a 3D printed microstructure, with a (2D) color printing on top. They measured their printer BRDFs using linear light source reflectometry [GTHD03]. Isotropic ink BRDFs and the height field were then iteratively optimized, taking shadowing and shading effects into account. Baar et al. [BSB*14] and Samadzadegan et al. [SBU*15] also suggested different approaches to fabricating spatially-varying gloss, although not in conjunction with gloss gamut mapping.

3. Scanning and fabrication

The scanning system comprises of a frame with two scanning modules, the 3D scanning module (described in [EZV*14]) and the gloss scanning module (described in [EEL*17])(see figure 2). These two modules are able to capture color, topography and gloss variations of a globally-flat surface. Components used for gloss scanning are: a camera with a rotating polarization filter, and an LED array with a diffuser, mounted at opposing mirror angles (see figure 2(b)). The gloss scanning module captures spatially-varying gloss by imaging the surface under Brewster's angle, which is defined by the refraction index of the material. The difference between a capture with reflections (parallel polarization) and without reflections (cross-polarization) provides a measure for the gloss variation. The measurement is corrected for illumination

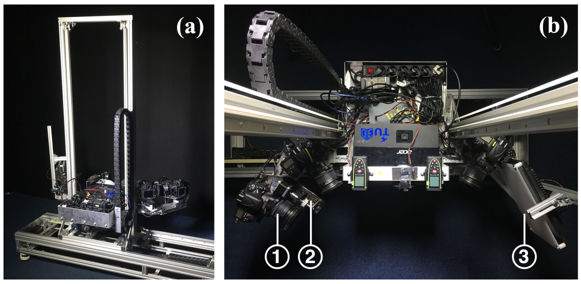


Figure 2: *Scanning system showing (a) the frame with the platform holding the two scanning modules and (b) a top view of the platform where the gloss scanning module consists of (1) a camera, with (2) a rotating polarization filter and (3) the LED array with a diffuser.*

non-uniformity, off-center specular measurements and shadowing, which is caused by local surface normal variations. An adapted version of Océ Technologies "Elevated Printing" technology [Oce17] is used for the fabrication of the material appearances which utilizes UV-curable inks. First, the 3D full color relief is printed with CMYK and White (CMYKW). Then, a transparent ink is used to create spatially-varying gloss through different amount of half-toned varnish layers at each position of the 3D full color relief [EEL*17].

4. Gloss calibration

For the purpose of gloss calibration, flat targets in the primary printer colors (CMYKW) were fabricated with increasing levels of uniform gloss. The targets were printed using the Elevated Printing Technology. Six equal-distant levels were created (11 for Cyan), based on 60 °gloss measurements of a set of test patches using a BYK micro-tri-glossmeter [BYK17]. Figure 3 shows four of the 35 targets. The input and output gloss values (measured with the glossmeter), are plotted in figure 5. The figure shows the average (left axis) and standard deviation (right axis) of the gloss values (60°gloss, in GU) of 5 measurements across the surface, per color. As the deviation of printed gloss values is small regarding the input values as well as the standard deviation (< 1.9), the targets will be treated as uniform and equal-distant for all colors. All gloss calibration targets were scanned and an area of 7250x3000 pixels (approx. 18x7.5cm) was cropped from all scans, approximating the full width and 4/5 of the scan height of a single capture (excluding a region with the target reference information). An 1-term exponential, monotonic function ($f(x) = ae^{bx} + c$) was fitted to means of the scanned gloss values in the cropped areas (to all colors individually and combined). The exponential function, provided the best prediction of the variance, with the lowest residuals (also see results in section 6). The fitted function (averaging all colors) was used to gamut map the gloss values of a painting scan to the printable glosslevels. A one-to-one gloss gamut mapping strategy was applied for in-gamut glosslevels, while clipping gloss values to the minimum and maximum value measured on the calibration cards (analogous to a *colorimetric* rendering intent in color printing). With this approach the in-gamut gloss contrast was preserved, while details were lost for out-of-gamut gloss. This approach was

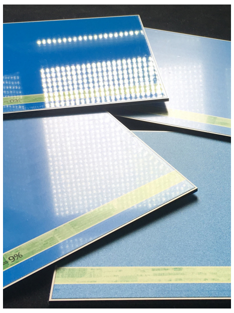


Figure 3: *Gloss calibration targets (cyan). Note the varying sharpness of the reflections.*

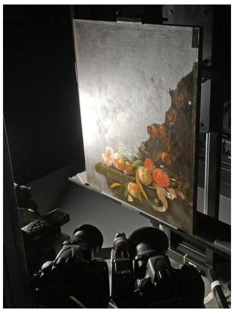


Figure 4: *Painting with partially removed varnish in front of the scanner.*

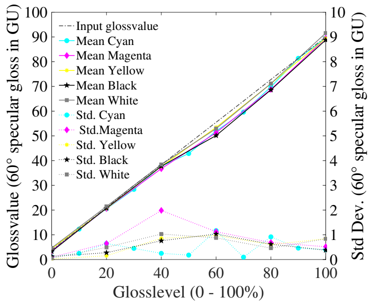


Figure 5: *60° specular gloss (in GU) of calibration targets, showing the mean (left axis) and standard deviation (right axis) of 5 points across the surface, per color.*

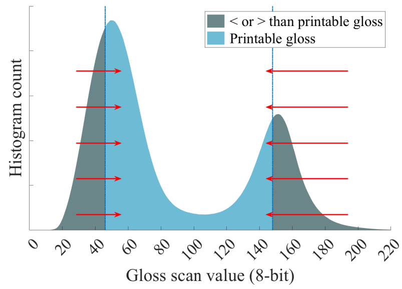


Figure 6: *Gloss scan values histogram of painting, showing values in- and outside the printable gloss range, which are clipped (arrows) to printable gloss range.*

chosen over an overall rescaling of the gloss gamut (analogous to a *perceptual* rendering intent), to be able to evaluate the ability to match the gloss in an absolute sense and reproduce local gloss contrast (for in-gamut gloss).

5. Case study

Our reproduction approach (incl. gloss gamut mapping) is applied to a painting named *Fruit Still Life* by Cornelis de Heem (c.1670), which is in the collection of the Mauritshuis, The Netherlands. The painting was undergoing restoration, where the varnish was already partially removed, providing two distinct regions: One glossy, varnished region, and a matte, unvarnished region, the latter showing some subtle gloss variations (see figure 1 and 4). Although not esthetically appealing, the high and low gloss regions provided a good test case for mapping gloss levels of the painting.

6. Results

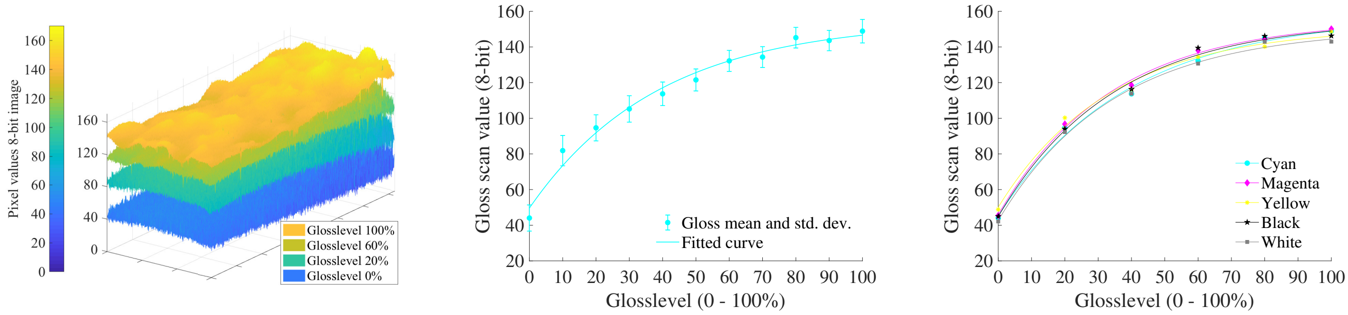
Figure 7(a) shows the surface plot of cyan gloss targets for 0%, 20%, 60% and 100% gloss. The highest gloss levels show some non-random variation across the surface (cloudy appearance, similar for all colors), which might be created by the lamp diffuser (shown in figure 2, the diffusion might be non-uniform). Figure 7(b) shows the means and standard deviations of the cyan gloss targets for 11 equal distant gloss levels, as well as the fitted exponential function The noise on the gloss measurement might be explained by that the printing resolution (450dpi $\approx$ 56µm) is lower than scanning resolution ($\pm$25µm), whereby the individual 'dots of ink' influence the gloss measurement. The noise is highest for matte targets, which have more dots placed side-by-side, versus more smooth high gloss print. In figure 7(c) the means of all colors are plotted at 6 equal-distant gloss levels, with their respective fitted curves.

The histogram of the gloss values measured on the painting, is plotted in figure 6. A distinct division is visible between the part where varnish is removed (highest peak) and the part that still has varnish (lower peak). It also shows the range of the printable gloss (blue), and the values clipped to the minimal and maximum printed gloss (dark green). Figure 1(a) depicts a detail of the painting, (b) the gloss scanning result, (c) the gloss scanning result mapped to printable gloss levels, and (d) a detail of the 3D reproduction including color, relief and gloss variations. Figure 1(a) and (d) were photographed under an angle, to be able to visualize the reflections on the surfaces. Clipping of gloss values to the minimal and maximum printable gloss did not seem to lead to obvious banding (a clear boundary at clipping edge) in (c) the gloss map or (d) the printed result .

7. Discussion and conclusions

The measurement of the calibration targets shows that gloss levels can be distinguished across the surface. However, the gloss measurements showed some systematic variations, which were similar across all colors. Part of the systematic variation seems to be caused by the non-uniformness of the LED diffuser, which causes 'cloudy' patterns. This pattern is more obvious in measuring the high gloss target than the lower targets, as the high gloss targets basically acts as a mirror and the lower gloss target diffuses lights. High frequency noise appears in all measurements, and might be explained by the printing resolution being lower than the scanning resolution, whereby individual print dots may influence the measurements. Furthermore, the planarity of the gloss measurement remains to be investigated. In this paper, only one gloss gamut mapping strategy has been implemented. The downside of the absolute mapping approach is that out-of-gamut details are lost and there is a potential for banding (a clear boundary at clip edge), although this was not obvious in the case study. More research is needed to determine perceptually relevant gloss mapping strategies. For instance, using the work of Ferwerda et al. [FPG01] or Obein et al. [OKV04] on perceptually uniform gloss scaling as a starting point. Moreover, the current approach implements a direct link between the gloss input device (scanner) and gloss output device (printer). Color gamut mapping links profiles through a device independent 'profile connection space'. The advantage of this is that the calibration can be done for the scanning and printing device separately, which makes it possible link any input device to any output device. An equivalent for gloss gamut mapping, has yet to be determined.

In this paper an approach is presented for the gloss calibration and gamut mapping, by using printed gloss targets to associate



(a) Surface plots of 0%, 20%, 60% and 100% gloss, of cyan calibration targets, sampling every tenth pixel

(b) Mean and std. dev. of sample area for glosslevels 0-100% on cyan calibration targets, with fitted curve

(c) Mean of sample area for glosslevels 0-100% on all calibration targets, with fitted curves per color

Figure 7: *Gloss scan value plots (8-bit pixel value) of gloss calibration targets, all sampling a region of 7250x3000 pixels, approximating a single capture tile. For (b), samples were created with 11 equal-distant steps and for (c) six steps, limiting printing cost and scanning time.*

printable gloss (output) to scan data (input). Results indicate that the gloss measurement approach is independent of the diffuse color. The mean gloss values were plotted and an exponential function was fitted to the data. The painting *Fruit Still Life* by C. de Heem was scanned, exhibiting high and loss gloss regions, due to partial varnish removal. The scanned gloss was mapped to the printable gloss using the function fitted to gloss calibration data and clipping to the minimum and maximum printable glosslevel (analogous to a colorimetric rendering intent). The mapped and printed result shows that the approach is able to reproduce the gloss details in the in-gamut range and does not show obvious banding effects, due to clipping. Limitations of the gloss calibration approach are also identified in terms of gloss measurement uniformity, gloss mapping strategy and gloss printing, which highlight the future work of the authors.

Acknowledgements

The authors would like to thank the Mauritshuis for providing access to the painting *Fruit Still Life* by Cornelis de Heem, used as a case study in this paper, and Océ Technologies for printing services.

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