EUROGRAPHICS Workshop on Graphics and Cultural Heritage (2017)
R. Sablatnig and B. Štular (Editors)

Short Paper

Reproduction of Gloss, Color and Relief of Paintings using 3D Scanning and 3D Printing

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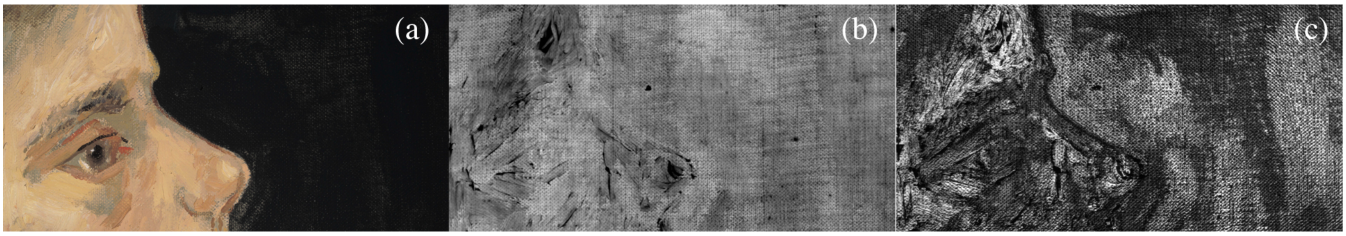

Figure 1: *Scans of part of a painting, showing (a) color, (b) height map and (c) gloss map, describing the appearance of the surface*

Abstract

High fidelity reproductions of paintings provide new opportunities to museums in preserving and providing access to cultural heritage. This paper presents an integrated system which is able to capture and fabricate color, relief and gloss of a painting's surface, emphasizing on gloss capturing. To measure the spatially varying gloss, the specular reflection of the center of the scanned area is sampled at the Brewster angle, utilizing the effect of reflectance polarization at this angle. The off-center gloss measurements are corrected using the perpendicular and parallel reflectance coefficients, relative to the center measurement. Shadows in the gloss map, which are caused by 3D relief of the surface, are masked based on the height map and then filled by interpolating surrounding gloss information. The captured color image, height map and gloss map are inputs for the 3D printer. A painting "Two wrestling figures in the style of Van Gogh" was reproduced to verify the effectiveness and efficiency of the proposed system. Experiment results indicate that the proposed system gives accurate enough gloss measurement of the painting's surface for the purpose of gloss fabrication.

CCS Concepts

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

1. Introduction

Increased capabilities of 3D-scanning and -printing systems provide new opportunities to create high-fidelity physical reproductions of artworks. Reproductions, in addition to the original artwork, can play an important role in museums' mission of preserving and providing public access to cultural heritage. Typical applications which support their mission include: Showing an artwork outside a museum, showing reconstructions of the original state of an artwork (e.g. [ELW*16]), creating records of an artwork in different stages of a restoration process, or selling high-end reproductions. All these applications require high-fidelity reproductions that closely resemble the artwork's appearance. In previous work [ZJLD14] a system was presented which is able to reproduce the color and relief (three dimensional height variations) of a painting's surface using 3D scanning and 3D printing technology. However, spatially varying gloss of the surface, which is a crucial component in the appearance of the painting, was still missing in these reproductions [EZV*14].

In this paper, we present an integrated system which is able to capture and fabricate color, relief and gloss of paintings, with the emphasis on gloss capturing. The paper is arranged as follows: in section 2, literature is briefly reviewed regarding appearance measurement and fabrication. Section 3 presents the system and the approach that is deployed to measure and fabricate color, relief and

DOI: 10.2312/gch.20171312

gloss. An experiment was conducted utilizing the proposed system and the results are presented in section 4. The advantages and limitation of the proposed system are discussed in section 5 and conclusions are drawn in section 6.

2. Related work

A 3D reproduction pipeline consists of capturing the appearance of a given artwork and fabricating this appearance. Various methods were developed for capturing spatially varying appearance of paintings and other globally flat surfaces (e.g. [PSM02] [GTHD03] [RM07] [RWS*11] [AWL13] [HTNI11] [TT08] [ELB*15]). These methods use a variety of capturing approaches and models to represent the surface appearance. These approaches generally require a (large) number of images to be able to accurately estimate the reflectance (model parameters) of each surface point. This is due to the fact that these appearance models are geared at computer rendering, and therefore require (high) angular accuracy to be able to make a good estimation of appearance at every viewing/rendering angle. It is argued that this level of angular accuracy is not necessary for creating physical reproductions. Contrary to the angular accuracy, it is necessary to have a high spatial accuracy for the reproduction (at least 300dpi), requiring close range imaging. At this resolution many existing methods are time consuming (in terms of data acquisition time) and/or computationally expensive, which limits their applications in 3D reproduction.

In fabricating spatially varying gloss (combined with color), several approaches have been demonstrated such as: Combining inks with various reflectance properties [MAG*09], combining a 3D printed micro texture with a (2D) color print on top [LDPT13]; changing the printer parameters to influence the micro-structure of printed droplets and thereby the gloss [BSB*14], or printing with a transparent ink on top of a color print [BBOS15] [SBU*15]. Printing with transparent ink seems the most applicable approach, as it uses limited types of materials and the process can be combined with relief printing (and potentially applied to 3D printing as well).

3. Materials and Methods

3.1. Materials

The scanning system consists of two modules: the 3D imaging module, which focuses on capturing color and relief, and the gloss scan module, focused on capturing the gloss. The major components for the 3D imaging module are two cameras and a projector ($C1$, $C2$ and P in Fig. 2a), all fitted with polarization filters to eliminate reflections (same config. as [ZJLD14], but projector is an Acer X133H). For the gloss scan module, an LED array with a diffuser (L), and a camera ($C3$) with a rotating polarization filter (RP) are mounted on the same platform. The platform is fitted to a frame, controlled by an Arduino® micro-controller (A). The frame is able to move the platform along X and Y axes (HF and VF) for scanning large paintings (max. 1.3 by 1.3m). All cameras are fitted with Scheimpflug lenses, to align the focal plane of the cameras with the painting surface. Fig. 2b shows the setup of the experiment.

An adapted version of Océ Technologies [Oce17a] "High Definition 3D printing" technology was used for printing [Oce17b]. The system is an inkjet printer, using UV-curable inks.

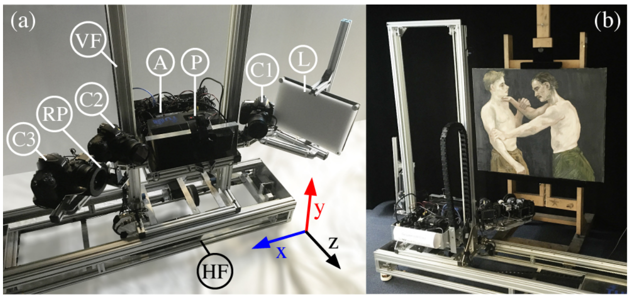

Figure 2: *The fine art scanner (a) components (as Section 3.1) (b) scanner in front of the painting*

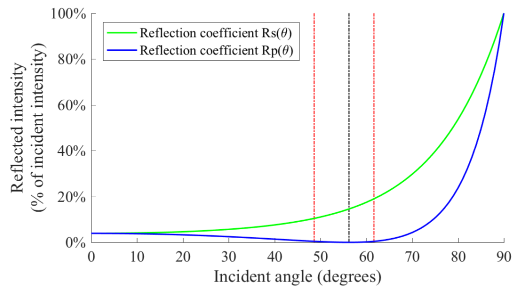

Figure 3: *Reflection coefficients R_s and R_p (n_2=1.495)*

3.2. Method

3.2.1. Color and relief capturing

The color and 3D relief of the surface are captured using a hybrid solution of fringe projection and stereo imaging (described in [ZJLD14]). The current setup is able to achieve an in-plane resolution of 25 µm × 25 µm (XY) and 10 µm in the height direction (Z), outputting a color image and a height map.

3.2.2. Gloss capturing

The gloss is captured by utilizing the polarizing of reflections. The intensity and polarization of reflections, can be calculated using the Fresnel equations [Hec02]:

$$R_s(\theta) = \left(\frac{n_1 \cos\theta_i - n_2 \cos\theta_t}{n_1 \cos\theta_i + n_2 \cos\theta_t}\right)^2 \quad (1)$$

$$R_p(\theta) = \left(\frac{n_1 \cos\theta_t - n_2 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i}\right)^2 \quad (2)$$

where reflection coefficients R_s and R_p correspond to the perpendicular and parallel directions to the surface. n_1 and n_2 are the refractive indexes of air and the material being scanned, θ_i and θ_t are the incident and transmission angles, whereby the latter can be substituted using Snell's law and trigonometric identities [Hec02]:

$$\frac{n_2}{n_1} = \frac{sin(\theta_i)}{sin(\theta_t)} \quad \Rightarrow \quad \cos(\theta_t) = \sqrt{1 - \left(\frac{n_1}{n_2}\sin(\theta_i)\right)^2} \quad (3)$$

The relations between reflection coefficients (R_s and R_p) and the

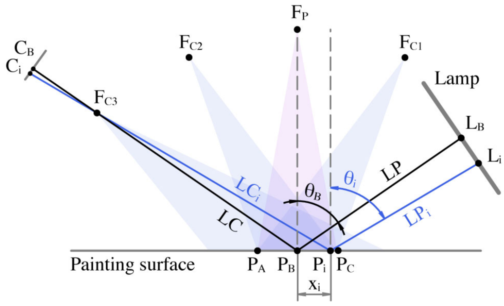

Figure 4: *Setup of the scanner (for details, see Section 3.2.2)*

incident angle are plotted in Fig.3 (for $n_2 = 1.495$). As reflection coefficient R_p goes to zero at the Brewster angle, the light is effectively polarized at (and around) this angle.

In gloss scanning, the area to be scanned is illuminated and the center is captured under the Brewster angle, where the reflected light is polarized. The measurement of the gloss is obtained by taking the difference between an image with reflections (parallel-polarized) and an image where the reflections are filtered using the rotational polarization filter in front of the camera lens (cross-polarized). This separates the reflection from the unpolarized diffusion of the painting as:

$$I_g = I_p - I_c \tag{4}$$

where I_g, I_p and I_c are the gloss map, the parallel-polarized image and the cross-polarized image, respectively. Differences in the intensity of I_g corresponds to gloss levels of different parts of the surface. The proposed approach assumes that the peak of the specular reflection is dominant over off-specular, scattered by micro-scale roughness of the surface. The Brewster angle [Hec02], where the reflection is fully polarized, can be calculated as follows:

$$\theta_B = \arctan(\frac{n_2}{n_1}) \tag{5}$$

Oil paints and varnishes that were often used in painting were found to have a refractive index between 1.47 and 1.52 [dlRDM*10], yield a Brewster angle between 55.8°and 56.7°. The averaged refractive index ($n_2 = 1.495$), which gives a Brewster angle (θ_B) of 56.3°, is then adopted in the setup of the system and data processing. In the setup of the scan modules (schematic top view in Fig.4), a diffuse light source (*Lamp*, which is a flat panel) is placed at the right of the figure to illuminate the surface of the painting. The camera is setup at the left of the figure. Given a point P_B in the painting, which is the center of the scanned area, the angle θ_B between the perpendicular direction of P_B (line F_p P_B) and the perpendicular direction of the light source is set as the Brewster angle. The angle between line F_p P_B and the optical axis of the camera is set as the Brewster angle as well. The width of a single gloss capture is approx. 180mm on the painting (distance between P_A and P_C in Fig.4). The different incident angles of point P_A and P_C yield different reflection coefficients R_s and R_p as shown in Table 1. At the boundaries 4.06% and 2.18% of the reflected light remains unpolarized, respectively.

To compensate errors of the measurement in the off-center area

Table 1: *Reflection coefficients for mirror reflection angles at left image boundary (P_A), Brewster angle (P_B) and right image boundary (P_C).*

	P_A	P_B	P_C
R_p coefficient	0.0044	0	0.0042
R_s coefficient	0.1045	0.1456	0.1899
$R_p/(R_p+R_s)$ error	4.06%	0%	2.18%

of the scan, gloss image (I_g) is converted from RGB to HSL color space first, where the lightness channel (L) is used as light intensity for further image processing. The intensity at any point in the painting (P_i) is scaled relative to the center of the image, for the irradiance arriving at that point (P_C is closer to the light source than P_A) (applying the inverse-square law [Hec02]):

$$\frac{E(P_B)}{E(P_i)} = \frac{LP_i^2}{LP^2} \quad \text{thus,} \quad E(P_i) = E(P_B)\frac{LP^2}{LP_i^2} \tag{6}$$

where $E(P_i)$ and $E(P_B)$ is the irradiance at P_i and P_B respectively, for distance LP_i and LP from the lamp to the surface. Then the intensity is scaled for the radiance reflected at every point, relative to the center of the scan, by using the difference between reflection coefficients as scaling factors:

$$L(P_i) = \frac{R_s(\theta_B) - R_p(\theta_B)}{R_s(\theta_i) - R_p(\theta_i}L(P_B) \tag{7}$$

where $L(P_i)$ and $L(P_B)$ is the radiance leaving point P_i and P_B respectively. R_s and R_p are reflection coefficients as a function of the incident angle (see Eq. 1, 2 and Fig.3).

Finally, the radiance arriving at the camera sensor is scaled for the differences in distance between the painting and the camera sensor, relative to the center of the scan as well (applying the inverse-square law [Hec02]):

$$\frac{L(C_B)}{L(C_i)} = \frac{LC_i^2}{LC^2} \quad \text{thus,} \quad L(C_i) = L(C_B)\frac{LC^2}{LC_i^2} \tag{8}$$

where $L(C_i)$ and $L(C_B)$ is the radiance from P_i and P_B respectively, for distance LC_i and LC from the surface to the camera optical center. Combining the above formulas, the reflectance intensity at any point can be described as:

$$I(C_i) = I(C_B)\frac{LC^2}{LC_i^2}\frac{R_s(\theta_B) - R_p(\theta_B)}{R_s(\theta_i) - R_p(\theta_i)}\frac{LP^2}{LP_i^2} \tag{9}$$

where $I(C_B)$ and $I(C_i)$ is the reflectance intensity in the image, corresponding to the gloss at point P_B and P_i respectively. Based on camera calibration matrix, using multi-view geometry, a gloss scan is mapped to the color image and the height map. Shadows in the gloss map are removed utilizing the height map as illustrated in Fig.5. Given an incident ray of light, due to the 3D structure of the painting, shadows may be created as the the gray pixels in the figure. Those gray pixels form the shadow correction mask. In the data processing, gloss information in the shadow correction mask were discarded and filled based on interpolating correct gloss information around the shadow (green and red pixels in the figure).

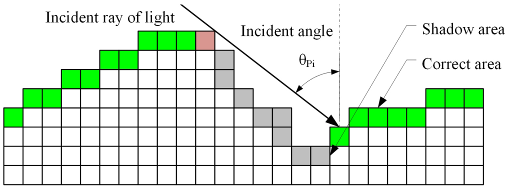

Figure 5: *Shadow removal using the height map*

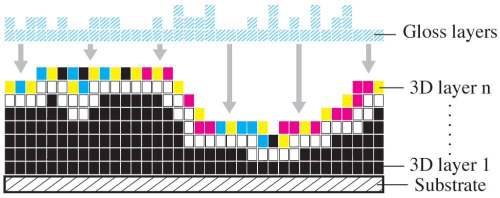

Figure 6: *Cross section view of the 3D print showing the substrate, relief/color layers, and gloss layers*

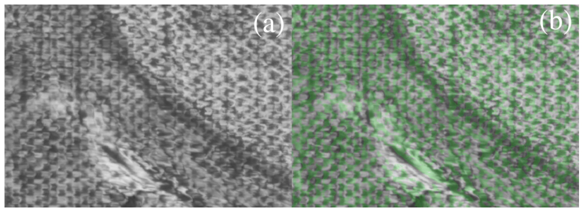

Figure 7: *A gloss scan(a) superimposed by the shadow mask(b)*

Figure 8: *The reproduction where gloss variations are visible*

3.2.3. Appearance fabrication

To fabricate the appearance, three input files are used: a color image, a height map (resembling the 3D relief) and the gloss map. The color image and height map are combined to form a stack of bitmaps, whereby the color of every surface point is printed in the layer corresponding to the height specified in the height map for that point. Thus, the color and relief are printed integrally using cyan, magenta, yellow, black and white ink (see Fig.6). Spatially varying gloss is printed in a second pass on top of the colored relief. To create spatially varying gloss, multiple layers of several transparent inks are deposited on the surface to vary the micro-scale roughness of the surface.

4. Results

A painting "Two wrestling figures in the style of Van Gogh" was used as a case study for the proposed reproduction system. Six scans (of 140 total) were processed and printed. Processing time of 1 scan is roughly 30 minutes. Examples of the color, the height map and the gloss map are shown in Fig.1. The maximum height differences in the height map 1(b) is 0.94mm. The gloss values 1(c) are mapped to the printer based on a linear mapping between the measured minimal and maximal scan values, and the minimal and maximal gloss printing values of the 3D printer. Figure 7(a) shows a zoomed part of the gloss map before the shadow correction was applied (see Section 3.2.2). In Fig.7(b), the shadow correction mask is superimposed on the gloss map in semi-transparent green. Figure 8 presents the 3D print of part of the painting where the gloss variations are visible.

5. Discussion

The proposed system demonstrates that it is possible to capture spatially varying gloss of a painting's surface with sufficient accuracy for 3D printing. Visual inspection indicates that the reproduction is able to authentically reproduce the color, relief and gloss of the painting.

A limitation of the current approach is that with heavily textured surfaces, a large portion of the gloss map is masked and has to be filled by interpolation, leading to less accurate results. This effect might be mitigated by merging scans taken from opposing angles, i.e., performing another gloss scan of the painting rotated 180°. Additionally, the gloss map is not corrected according to the local surface normal, as measurement angles of 3D reliefs may differ from the theoretical incident angle, which is calculated based on the assumption that the painting is a 2D planar surface. Though we did not discover major differences, the scale of this effect can be further inspected. Additionally, the color (in)dependency of the gloss measurement should be investigated.

In terms of fabrication, the measured gloss values are mapped to the the full range of printable gloss levels via a linear mapping. Scanning printed reference samples may discover better relations between the measured gloss values and the printable gloss levels. Additionally, further quantitative and qualitative evaluation of the reproductions should be conducted to validate the scanning and printing results.

6. Conclusions

In this paper, we present a painting reproduction system with the focus on gloss capturing. The spatially varying gloss of a painting is measured by sampling the specular reflection close to the Brewster angle. A mathematical model is developed to correct off-center deviations of the gloss measurements. Shadows are masked by the height map and filled with relevant gloss information. Experiment results indicate that the proposed system is able to reproduce the color, the 3D relief and especially the gloss information of a painting. Limitations of the system are also identified regarding the shadow mask, surface normals, color dependence, and relations between gloss measurements and printable gloss levels, which highlight the future work of the authors.

7. Acknowledgment

The authors would like to express their appreciation to the team of 'Het Geheim van de Meester' for providing the painting "Two wrestling figures in the style of Van Gogh" which was used as a case study in this paper.

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