A Multiscale Analysis of the Touch-Up Problem

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Abstract

In the commercial paint industry, differences in application methods can lead to what is known as the "touch-up problem", where two regions coated with exactly the same paint look different in color, gloss, or texture. In this paper we investigate the causes of the touch-up problem and identify physical and visual factors that contribute to it. First, we create samples by applying a flat white latex paint to standard gypsum wallboard. Two application methods: spraying and rolling are used. We then measure the BRDFs and textures of the samples and find differences at both the microscale and mesoscale that help explain the effects. Next we use the BRDF and texture data as input for a physically-based image synthesis algorithm, to generate realistic images of the surfaces under different viewing conditions. Finally we discuss ongoing work to use these computer graphics methods to generate stimuli for perceptual studies, and to develop a psychophysical model of the touch-up problem that relates physical differences in paint formulation and application methods to visual differences in surface appearance. The purpose of the model is to provide guidance for the development of methods to minimize the touch-up problem.

Introduction

In the commercial paint industry differences in paint application methods can lead to the "touch-up problem", where two coats of paint, a base coat and a top, touch-up coat, look different in appearance even though the paints used are exactly the same. The touch-up problem may manifest itself as differences in color, gloss, and/or texture between the base and touch-up regions and the differences can vary with surface illumination and viewing conditions.

Figure 1 shows an example of the touch-up problem. Here during construction, a wall in an office hallway was spray painted with a base coat of matte white paint. Over time spots on the wall were scratched or otherwise damaged and a touch-up coat of the same paint was applied locally with a fabric roller. When the wall is viewed straight on, the base and touch-up regions match reasonably well. But when the wall is viewed obliquely with grazing illumination (as is often the case in a hallway), the base and touch-up regions differ significantly in appearance, revealing the repairs and reducing the perceived quality of the repair job. In architectural applications, the touch-up problem is a significant and costly problem for both the paint and construction industries, The problem extends to other fields as well, such as automotive manufacturing and repair.

In this paper we conduct multiscale analysis of the touch-up problem. Our approach has three components: measurement, modeling, and simulation.

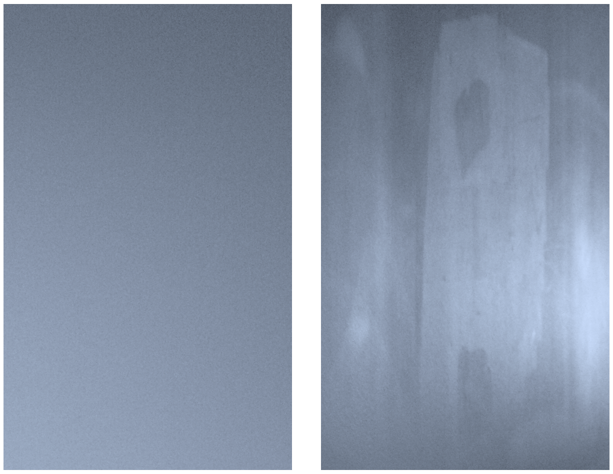

Figure 1. The touch-up problem. The left panel shows a section of a white, matte painted wall viewed straight-on. The right panel shows the same section of the wall viewed obliquely. Note the differences in surface lightness and gloss in the base and touched-up regions.

- We first measure the microscale reflectance properties of flat painted surfaces using a goniospectrophotometer. We also measure the mesoscale textures of the surfaces using photometric stereo methods.
- We then fit the reflectance data with the Cook-Torrance BRDF model and calculate surface normal maps to represent the mesoscale textures.
- Using these models we then render synthetic images of the surfaces using computer graphics image synthesis techniques. Through computer graphics, we can vary the parameters of the models to produce systematic variations in paint color, gloss, and texture and render images that show differences in the micro- and mesoscale reflectance properties of these paints under different illumination and viewing conditions.

The goal of these efforts is to use the rendered images as stimuli in a series of perceptual experiments to investigate how the appearance of painted surfaces changes with variations in physical surface properties and environmental lighting and viewing conditions The results of these experiments can then be used to develop a psychophysical model of the touch-up problem to predict how differences in paint formulation and application methods affect severity of the problem, and to develop strategies for minimizing or mitigating it.

In the following sections we first provide some background on paint and its properties, and describe our measurement and modeling techniques, and computer graphics rendering methods. We then discuss the specifics of our measurement, modeling, and rendering efforts and the insights they have provided about the causes of the touch-up problem. Finally we discuss the contributions and limitations of the research, and directions for future work.

Background

Paint

Paint is a ubiquitous material in the built environment. Paint serves as a surface finish for a wide range of materials including wood, stone, metal, paper and others. Many different kinds of paint have been created including oil-based alkyds, water-based latex, acrylics, tempera, and encaustics. Two main factors affect paint appearance: formulation and application [ASTM09].

Although paints differ widely in the components used in their formulation, they all consist of pigment particles suspended in some kind of liquid binder. Differences in particle and binder properties lead to the wide variations in color and gloss seen in different kinds of paint. Unusual formulations can also be used to produce “special effects” such as metallic sparkle and luster, surface crinkle, and goniochromatic shifts.

The other main factor affecting the appearance of painted surfaces is the method of application. The classic method is with a brush, and different types of brushes can produce relatively smooth surfaces or ones with significant relief or “impasto”. In architectural construction popular application methods include airless spraying and use of a fabric roller. Spraying is a very efficient application technique for covering large areas. Due to the fine drop size and random drop distribution, it tends to produce surfaces with a uniform “noisy” texture. Rolling is a simple method for that requires minimal equipment and depending on the nap of the roller can produce finishes with a wide range of textures from fine to large scale. Backrolling is a hybrid technique in which the paint is applied with a spray gun, but then the wet paint is rolled to finish the surface. In the construction process spraying is often used to apply a base coat, then backrolling is used to touch-up any defects.

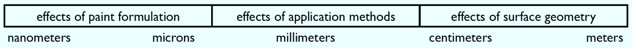

Figure 2. Diagram showing the relationships between paint appearance effects and spatial scale.

As a material paint seems homogeneous and simple, but this simplicity hides complex chemical, physical and optical properties, and the final appearance of a painted surface depends on processes that occur in different modalities at many spatial scales. This is illustrated in Figure 2. At the finest (nanometer/micron) scale there are the reflectance properties of the pigment particles that affect both spectral and directional light scattering at the microscale. As the paint dries and the binder evaporates, particle shape also comes into play affecting how the particles aggregate on the surface. At the mesoscale (~millimeters) paint application methods such as spray or rolling, and the texture of the substrate come into play, affecting the thickness and relief of the paint surface. Finally large-scale surface geometry (~centimeters/meters) can also play a role, with paint coats forming differently on flat, curved, horizontal and vertical surfaces.

Measuring surface reflectance

One factor that affects the appearance of a surface is its reflectance properties. For homogenous surfaces, color is related to the surface’s spectral reflectance and gloss is related to its directional reflectance. The directional reflectance properties of a surface are characterized by the bidirectional reflectance distribution function (BRDF), that parameterizes how light is reflected by a surface as a function of the angle of incidence, the angle of reflection, and the surface tilt. BRDFs are typically measured with a goniophotometer [Nicodemus77].

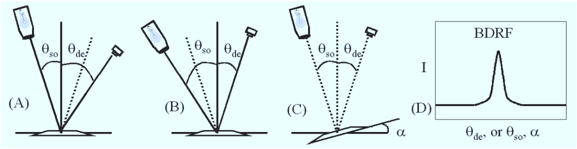

Figure 3: A goniophotometer measures reflected light as a function of (A) the angle of detection θde; (B) the angle of illumination θse; and/or (C) the angle of tilt of the sample, α. Each produces a bi-directional reflectance factor function, BRDF, illustrated in (D) (From [1]).

Figure 3 shows the basic source, sample, detector geometry of a goniophotometer and one of the BRDF curves that is generated when one of the three factors is varied. Most goniophotometers are averaging instruments, which means that their detectors have finite sampling apertures and that all surface features that fall within the aperture will have an impact on the measured BRDF. This can be an important factor when a surface is patterned or textured. Imaging goniophotometers that use high resolution digital cameras in place of simple detectors are being developed to allow the measurement of surfaces with spatially-varying BRDFs [Berns10].

Measuring surface topography

Significant information about the visual appearance of a surface can be derived from measures of its topographic features. Contact profilometry is a mechanical method for measuring topography that uses a fine stylus connected to a pen to trace out surface relief. Optical interferometry uses Moire fringes generated by light patterns reflecting from a surface to infer surface height. Photometric stereo is an image-based technique for measuring surface topography that comes from the field of computer vision [Woodham80].

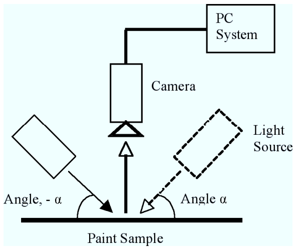

Figure 4 Equipment setup for photometric stereo measurement of surface topography.

Figure 4 shows a basic photometric stereo setup. The surface to be measured is placed horizontally on a base. A camera is mounted above the surface pointed downward. Lights are placed on either side of the surface. A pair of images is taken of the surface lit from each direction, then the surface is rotated 90^{o} and a second pair of images is taken. Assuming the surface has a matte finish and the camera has a linear response, a surface normal map can be calculated from differences in the pixel values in the left/right illuminated image pairs. Height fields can also be estimated through integration of the normal maps.

Computer graphics modeling and rendering

Computer graphics image synthesis techniques offer a powerful set of tools for studying surface appearance. Over the past thirty years computer graphics modeling and rendering methods have developed from creating crude representations of simple geometric shapes to being able to produce radiometrically accurate simulations of surfaces with complex shapes, textures and material properties situated in rich natural lighting environments [Greenberg97].

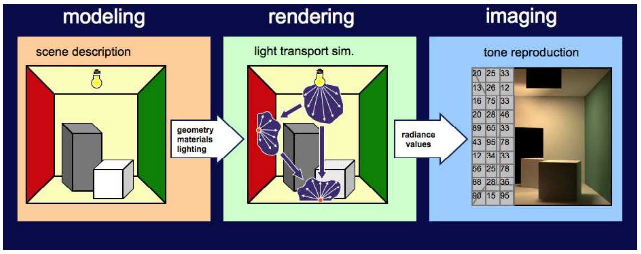

Figure 5. The image synthesis pipeline (after Greenberg et al. 1997).

The basic image synthesis pipeline is illustrated in Figure 5. First, in the modeling stage, a mathematical model of the scene in created by describing the 3D surface geometry, surface reflectance properties, and emissive properties of the light sources. Material properties are described using light reflection models such as the Phong, Ward, or Cook-Torrance models that parameterize surface BRDFs.

In the rendering stage the model serves as input to a light transport algorithm that simulates how light propagates through the scene. Advanced path-tracing algorithms accurately simulate both direct illumination effects from light sources and indirect illumination effects from surface inter-reflections. The result is a simulation of the radiance values at each visible point in the scene.

Finally in the imaging stage this radiometric simulation is transformed by tone and gamut mapping algorithms for presentation on a display. The goal is often to produce an image that accurately represents the visual appearance of the scene for a human observer.

Physically-based image synthesis techniques provide a powerful tool for conducting psychophysical experiments on surface and material perception. By systematically varying the parameters of the surface geometry and BRDF models, and by changing lighting and viewing conditions it is possible to produce images that accurately represent the changes in surface optical properties. These images can then be used as stimuli in perceptual experiments to derive psychophysical models that can relate surface physics and visual appearance.

Analysis of the touch-up problem

Sample preparation

A touch-up sample was created by applying flat interior latex house paint to a 2' square panel of standard paper coated gypsum wallboard. Airless spraying was used to apply the base coat. Once the base coat had dried, a 1' square region in the center of the panel was "touched-up" with a second coat applied with a fabric roller.

To verify that the sample produced a measurable touch-up effect we photographed it with a digital camera (Canon EOS Xsi, 105mm lens, ISO 100, f29, cr2 raw image format, green channel extracted) from a distance of 1m and an angle of 60^{o} off the surface normal, and illuminated it with an point light source (white LED) positioned at a range of angles between 45^{o} and 80^{o} off the surface normal and opposite to the camera. Figure 6 shows the series of images produced by focusing on an edge between the sprayed based region (left half of each image) and the rolled touch-up region (right half of each image). Notice that distinct differences in surface lightness and texture can be seen between the two regions, with the base region generally appearing smoother and lighter than the touch-up region.

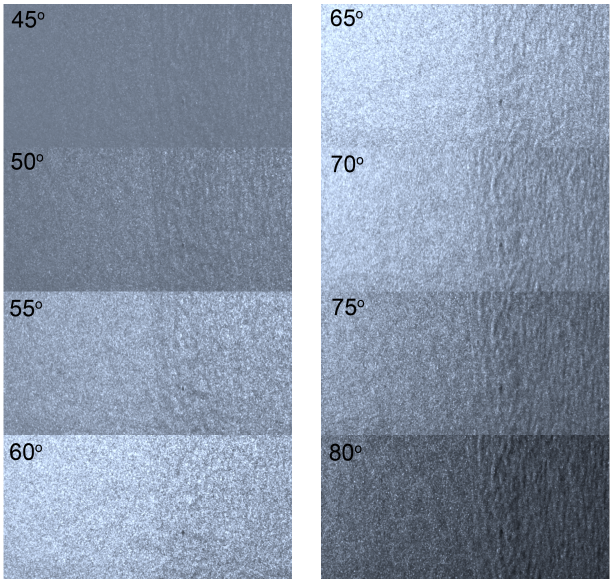

Figure 6. Cropped photographs of an edge between the sprayed base (left half of each image) and rolled touch-up (right half of each image) regions of the sample. Viewing is oblique at 60^{o} off the surface normal. Each panel shows the appearance at a particular illumination angle. Note the differences in visible surface texture and lightness that occuras the illumination goes from near normal (45^{o}) through specular (60^{o}) to grazing (80^{o}).

Reflectance measurements

At the microscale level, surface reflectance can be described using the bidirectional reflectance distribution function (BRDF), that characterizes how the surface scatters incident light. BRDF measurement of the base and touch-up regions of the samples was done using a Murakami GSP-1B goniospectrophotometer. In-plane measurements with source angles at 15, 30, 45, and 60 degrees were taken. The results are shown in Figure 7.

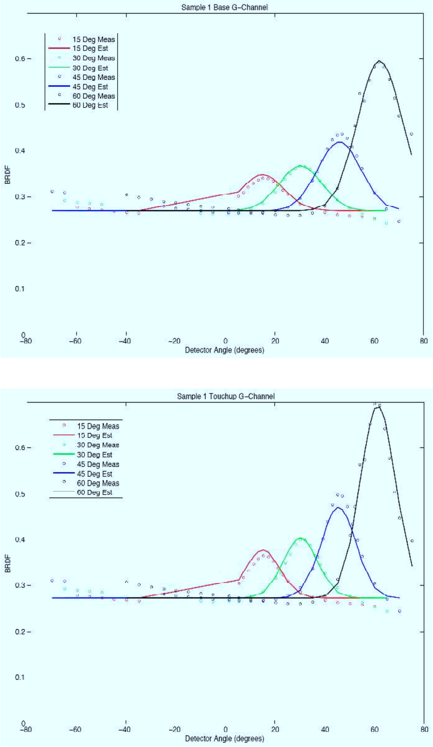

Figure 7. BRDF measurements for the a, top) sprayed base and b, bottom) rolled touch-up regions.

In Figure 7a the open circles show the data for the base region. Note that the magnitude of the specular reflection (when detector angle equals source angle) increases with source angle due to Fresnel effects that cause an otherwise matte surface to appear glossy when viewed at grazing angles. Note also, that the wide spreads of the distributions indicate that even at grazing, the surface has relatively low gloss.

Figure 7b shows the data for the touch-up region. Note that the touch-up region shows the same basic behavior with change of source angle, but also note that each of the distributions for the touch-up region are higher and narrower than those of the base region. **This indicates that over the range of spatial scales measured by the goniospectrophotometer, the touch-up region is optically smoother than the base region. This is confirmed by the visual appearances of the two regions, with the touch-up area looking glossier than the base.**

Topographic measurements

In addition to its reflectance properties, significant information about the visual appearance of a surface can be derived from its topographical features. Measurement of the mesoscale textures of the base and touch-up regions of the sample was performed using photometric stereo to derive surface normal maps.

The experimental setup is illustrated Figure 4. Images of the sample were captured with the illumination coming from each of the cardinal directions. The angle of illumination (α) was maintained at 32° from the horizontal plane. The camera field of view was 36.8mm, therefore the scaling obtained was approximately 0.07mm/pixel. Representative images showing the texture differences of the base and touch-up regions are shown in Figure 8.

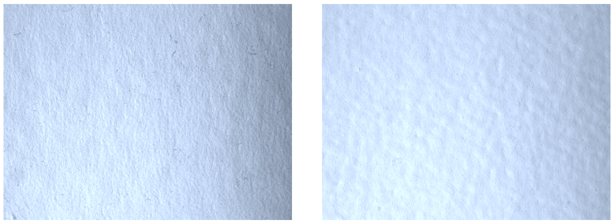

Figure 8. Images of a sample obtained as part of the photometric stereo method. a, left) sprayed base coat, b, right) rolled touch-up coat.

Standard photometric stereo techniques were used to derive surface normal maps. A noise power analysis of the frequency distribution of the normal angles was then performed in order to characterize the scales of texture elements on the surface. Figure 9 shows a graph of the noise power of the base and touch-up regions (WBjj and WTjj respectively) in terms of the spatial frequency of the elements (ξjj) in cycles/mm.

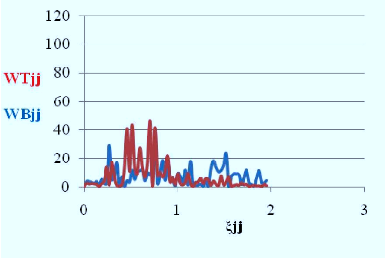

Figure 9. Noise power spectra of the base (WB, blue) and touch-up (WT, red) regions. Note that the spectrum for the touch-up region is concentrated at lower spatial frequencies.

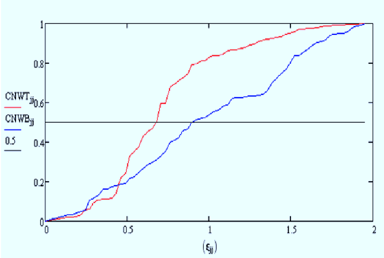

Figure 10. Cumulative noise power spectra for the base (WB, blue) and touch-up (WT, red) regions, The spectrum for the base is approximately linear (white noise-like) while the touch-up region has relatively more energy at low frequencies

Comparison of the two regions shows that the base region has a more even distribution over a wide range of frequencies than the touch-up region, which has more energy over a band of lower frequencies. The same phenomenon is reflected in the cumulative normalized noise power spectra (CNWBjj and CNWTjj) for the

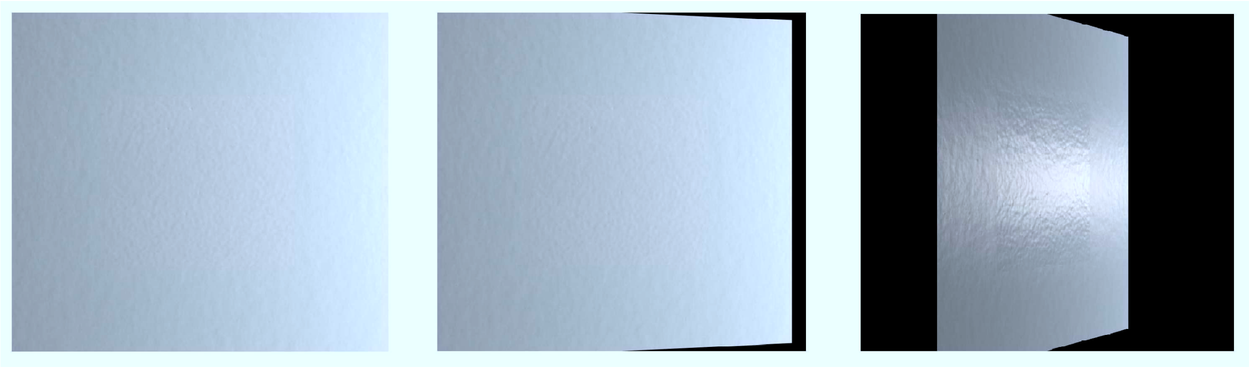

Figure 12. Renderings obtained with camera at 0° (left), 15° (middle) and 60° (right)

two regions shown in Figure 10.

These texture differences relate to the appearance differences seen in Figure 8. **Here at the mesoscale, the backrolled touch-up region looks rougher than the sprayed base region. It is curious to note that this is opposite to the result from the BRDF measurements, where the touch-up region was found to be smoother than the base.**

Modeling and Rendering

Using the BRDF data gathered in the measurement phase, we modeled the reflectance properties of the base and touch-up regions using the Cook-Torrance light reflection model. This model was used because of its effectiveness in handling nearly diffuse materials, such as the paint samples and its modeling of Fresnel effects. The solid lines in Figure 7 shows the fits obtained to the BRDF data using the Cook-Torrance model. Overall in the forward scattering direction (positive detector angles) the fits are good. Some backscattering effects (at negative detector angles) are not fit by the model but these are relatively minor.

Physically-based computer graphics rendering techniques were used to create synthetic images of the painted samples. Geometric representations of the center-surround panels were created using the normal maps, material properties were set using the Cook-Torrance fits to the BRDF data. The resulting models were illuminated with a simulated point light source placed 10 feet from the surface at an angle of 60 degrees to the surface normal, as shown in Figure 11.

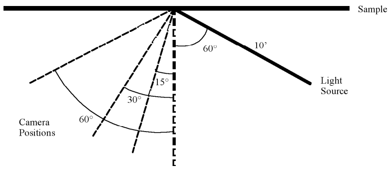

Figure 11 Rendering layout used to generate the synthetic images.

Figure 12 shows the synthetic images of the sample generated by this process. From left to right the images show the surface viewed at 0, 15 and 60 degrees with respect to the normal. At a standard 14 inch document viewing distance, the scale of features in the images is equivalent to viewing the sample from approximately 3 feet. Note that the simulations capture the touch-up phenomenon, where the base and touch-up regions are indistinguishable at near-normal viewing angles, but the touch-up region looks glossier that the base when illuminated and viewed from oblique angles.

Conclusions and Future Work

We are currently working to use the computer graphics techniques demonstrated above to generate stimuli for a series of perceptual experiments to study the relationships between surface reflectance, geometry, illumination, and viewing conditions and the visual qualities and magnitudes of the touch-up problem. In the experiments we will systematically vary each of these factors and analyze how they affect the visibility of the touched-up regions. We are doing pilot work to understand the critical spatial scales that contribute most to the touch-up problem. To do this we are taking advantage of the power of computer graphics to separate effects due to BRDF from effects due to texture.

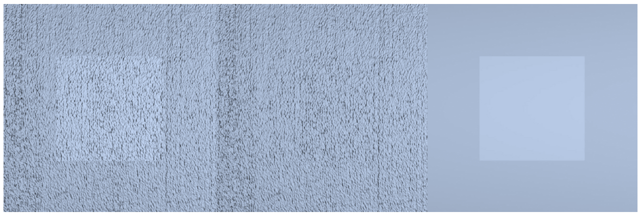

Figure 13. Contributions to the touch-up problem. Texture and BRDF differences (left), texture differences alone (center), BRDF differences alone (right).

Figure 13 shows an example where the image on the left shows a standard rendering of a panel with base and touch-up regions, and the images in the center and on the right show the individual contributions of texture and BRDF differences. **This is an interesting result suggesting that BRDF differences contribute most to the touch-up problem, however it also raises the issue of how texture and BRDF measurements relate to each other since due to its large acceptance angle, the sensor in the goniospectrophotometer is incorporating the effects of mesoscale texture variations into its BRDF estimates.** We are current teasing these effects apart in perceptual experiments to determine the critical spatial scales that contribute most to the touch-up problem.

Using the results of the perceptual experiments we will develop a psychophysical model of the touch-up problem for painted architectural surfaces that will relate the physical properties of the surfaces to their visual appearances. This model can then be used to allow paint manufacturers, architects, designers, and contractors to understand how and why the touch-up problem occurs, and to determine how to adjust formulations and/or application methods to minimize the problem.

Acknowledgements

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References

[1] J.S. Arney, A. Peter, and H. Hoon, A Micro-Goniophotometer and the Measurement of Print Gloss. Journal of Imaging Science & Technology, 48. (2004).

[2] ASTM, Standard practice for evaluating touch-up properties of architectural coatings under various environmental conditions. D7489-09. ASTM International, West Conshohocken, PA. (2009)

[3] J.A. Ferwerda, F. Pellacini, F, and D.P. Greenberg, A psychophysically-based model of surface gloss perception. Proceedings SPIE Human Vision and Electronic Imaging '01, 291-301. (2001).

[4] J.A. Ferwerda, G. Ramanarayanan, K. Bala, and B.J. Walter, Visual Equivalence: an object-based approach to image quality. Proceedings IS&T 16th Color Imaging Conference, 347-354. (2008).

[5] D.P. Greenberg, K.T. Torrance, P. Shirley, J. Arvo, J.A. Ferwerda, S. Pattanaik, E. Lafortune, B. Walter, S. Foo, B. and Trumbore, A framework for realistic image synthesis. ACM Transactions on Graphics (SIGGRAPH ’97), 477-494. (1997).

[6] F.E. Nicodemus, J.C. Richmond, and J.J. Hsia Geometrical Considerations and Nomenclature for Reflectance National Bureau of Standards, Washington, DC 20234. (1977).

[7] F. Pellacini, J.A. Ferwerda, and D.P. Greenberg, Toward a psychophysically-based light reflection model for image synthesis. Proceedings SIGGRAPH ’00, 55-64. (2000).

[8] R.J. Woodham, Photometric method for determining surface orientation from multiple images. Optical Engineerings 19, I, 139-144. (1980).

[9] D.R. Wyble, and R.S. Berns, Validating the Accuracy of the MCSL Imaging Goniospectrometer, Rochester Institute of Technology, College of Science, Center for Imaging Science, Munsell Color Science Laboratory, Rochester, New York, United States. TR-2010-01. (2010).