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APPEARANCE TRANSFORMATION OF 3D OBJECTS DEPICTED IN IMAGES[1]

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Abstract

In this work we discuss a method that facilitates transport of the material appearance between objects depicted in two different images. This is helpful in process of surface appearance design. We propose an approach that requires two steps performed on both source image capturing the object material, and target image capturing the object of interest. Firstly, the diffuse and specular reflection components are separated by removing specular highlights from the source image. Secondly, diffuse component of both input images is separated to obtain the surface normals of depicted objects. This is achieved by a shape from shading algorithm. Shape from shading algorithms are based on the fact that reflection of diffuse surface depends on its orientation to a light source. Thus the limitation of our approach is given by precise estimations of surface normals and the light direction needed to acquire a reflectance of depicted objects. Diffuse and specular components of a pixel within the target image are changed to achieve appearance of the object in the source image.

As this process contains some ambiguities, we do some assumptions about the scene depicted in these images. We assume smooth objects lit by a white directional light source. Diffuse color of objects is different then white. We also assume that there is a specular highlight depicted within images.

We have tested our approach on the multiple synthetic images with captured real car paints that were transferred onto an image of abstract 3D shape.

Mathematics Subject Classification 2000: I.3.6, I.3.7
Additional Key Words and Phrases: shape from shading, appearance, reflection components separation

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1. INTRODUCTION

The reflection model can be described as a function including various parameters related to color and geometry. Models for describing light reflection on an object surface are called *illumination models* and are widely used for rendering realistic images. In practice it could be useful to recover unknown reflectance properties from image data. Although the nature of the problem of recovering unknown reflectance parameters from image is underconstrainted, there are some works devoted to this problem. In [Robles-Kelly and Hancock 2005] is described a method for estimating surface radiance function from single images of smooth surfaces made of materials whose reflectance function is isotropic and monotonic. Under conditions in which the light source and the viewer direction are identical, this method can estimate a tabular representation of the surface radiance function. Classification of reflectance properties of surfaces from an image based on predictable statistics of the typical natural illumination is described in [Dror et al. 2001]. Properties of the object's surface reflection in [Tominaga and Tanaka 2000] are obtained by the color histogram analysis. In the process of the reflection analysis it is reasonable to separate the specular and diffuse reflection. Papers [Tan and Ikeuchi 2005] and [Tan et al. 2006] discuss the problem of this separation.

In this paper we present a problem of transfering a material appearance between two objects in images and solution of this problem under certain simplifying assumptions. To our knowledge there is no work devoted to this specific problem so far. Although, for the sake of simplicity we assume that depicted objects are lit by the white light source, the method [Tan et al. 2004] to estimation of the color of the illuminant could be used in general case.

2. SEPARATION OF THE SPECULAR COMPONENT

In the dichromatic reflection model the color of highlight is described as a linear combination of specular and diffuse color. This model proves adequate for most materials such as inhomogeneous dielectric. Under the assumption that the scene is lit by the white source and the diffuse color of the object is not desaturated, the diffuse component can be obtained by the projection along the illumination direction. Color of pixels in the specular highlight region of the image creates an highlight cluster in RGB space. See Figure 1.

Maximum chromaticity is defined by the following formula:

$$\sigma(\mathbf{x}) = \frac{max(I_{\mathrm{r}}(\mathbf{x}), I_{\mathrm{g}}(\mathbf{x}), I_{\mathrm{b}}(\mathbf{x}))}{I_{\mathrm{r}}(\mathbf{x}) + I_{\mathrm{g}}(\mathbf{x}) + I_{\mathrm{b}}(\mathbf{x})} \tag{1}$$

where $\mathrm{I_r}(\mathbf{x})$, $\mathrm{I_g}(\mathbf{x})$ and $\mathrm{I_b}(\mathbf{x})$ are R, G and B components of the pixel at the image coordinates $\mathbf{x}$. Desaturated pixels have greater maximum chromaticity then saturated pixels. Let $\mathbf{d}$ is a vector in the RGB space defined as $(\mathrm{I_r}(\mathbf{x}),\mathrm{I_g}(\mathbf{x}),\mathrm{I_b}(\mathbf{x}))$ where $\mathbf{x}$ are coordinates of the pixel of the object in the image where $\sigma(\mathbf{x}) = \max\{\sigma(\mathbf{y})|\mathbf{y}\in \Omega\}$. Ω is a region in the image where the object is inhered in. At coordinates $\mathbf{x}$ lies its most desaturated pixel. Let $\mathbf{s}$ is vector in the RGB space defined as (1,1,1). This represents the direction of the illumination color. Diffuse component $\mathbf{c}(\mathbf{x})$ of the pixel at the coordinates $\mathbf{x}$ with the color $\mathbf{p}(\mathbf{x})$ in the highlight cluster is then computed as the intersection of the line in the direction $\mathbf{s}$ from the image color $\mathbf{p}(\mathrm{x})$ with the line in the direction $\mathbf{d}$ from (0,0,0). Let $\mathbf{c}(\mathbf{x})$ is a color in RGB space obtained by following formula:

$$\mathbf{c}(\mathbf{x}) = \mathbf{p}(\mathbf{x}) + \mathbf{s}\frac{(-\mathbf{p}(\mathbf{x}) \times \mathbf{d}).(\mathbf{s} \times \mathbf{d})}{\|\mathbf{s} \times \mathbf{d}\|^2} \tag{2}$$

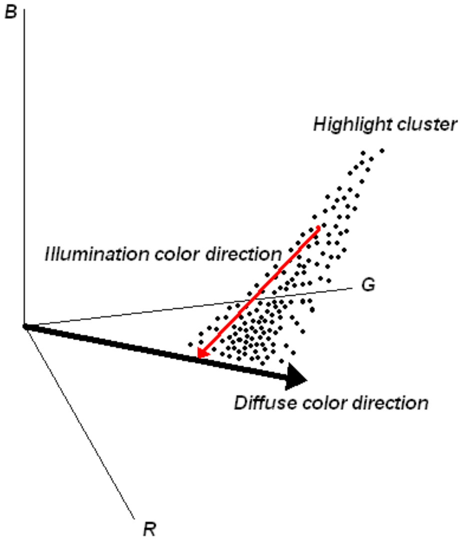


Figure 1. Color histogram in the RGB space.

Thus $\mathbf{c}(\mathbf{x})$ represents the diffuse component of the pixel at the coordinates $\mathbf{x}$ with the color $\mathbf{p}(\mathbf{x})$. Specular component is then subdivision $\mathbf{p}(\mathbf{x})$ - $\mathbf{c}(\mathbf{x})$. Figure 2 shows image of the sphere and images with the pixels decomposed into the diffuse and specular components.

As clamping in the color space produces saturation of the color, it is reasonable to use one of the HDR formats such as RGBE.

To evaluate errors we use mean square error. We have decomposited specular and diffuse component of the sphere. We also rendered specularfree sphere and have compared it with result of decomposition. We have evaluated error of the diffuse component to 2.10^{-6}. Error was evaluated by the following formula:

$$e = \frac{1}{|\Omega|} \sum_{\mathbf{x} \in \Omega} (\Delta(\mathbf{x}))^2 \tag{3}$$

where $|\Omega|$ is amount of pixels in region Ω of images and Δ is distance between two RGB colors.

$$\Delta(\mathbf{x}) = \sqrt{(I_{\mathrm{r}}(\mathbf{x}) - I'_{\mathrm{r}}(\mathbf{x}))^2 + (I_{\mathrm{g}}(\mathbf{x}) - I'_{\mathrm{g}}(\mathbf{x}))^2 + (I_{\mathrm{b}}(\mathbf{x}) - I'_{\mathrm{b}}(\mathbf{x}))^2} \tag{4}$$

Each component of the RGB color varies from 0 to 1. I'($\mathbf{x}$) is specularfree rendered image and I($\mathbf{x}$) is acquired diffuse component image. Mean square error of the specular component was 10^{-5}.

3. SHAPE FROM SHADING

Let $\mathbf{I}(\mathbf{x})$ is grayscale image of the diffuse component, then according to Lambertian reflection it can be written as

$$\mathbf{I}(\mathbf{x}) = \eta(\mathbf{N}(\mathbf{x}).\mathbf{L}) \tag{5}$$

where $\mathbf{L}$ is the illumination direction, η is the composite albedo and $\mathbf{N}(\mathbf{x})$ is the surface normal at the image plane coordinates $\mathbf{x}$. Obtaining of the 3D shape from a single shaded image is ill-proposed problem, therefore most algorithms incorporate regularization. The common assumption about surface shape is that the surface is locally spherical.

Most shape from shading methods in [Zhang et al. 1999] require knowledge of direction of illumination. In [Zheng and Chellapa 1991] are discussed some methods for estimation of the illumination direction and albedo. These methods are based on the statistics of derivatives of image intensities in particular directions. Although for the images of perfect sphere these methods work quite well, for relatively complex images results are not very encouraging. The recovered shape can be expressed as depth Z($\mathbf{x}$) or surface normals where Z axis pints toward the camera. An iterative method based on the discrete approximation of the surface gradients is proposed in [Tsai and Shah 1994].

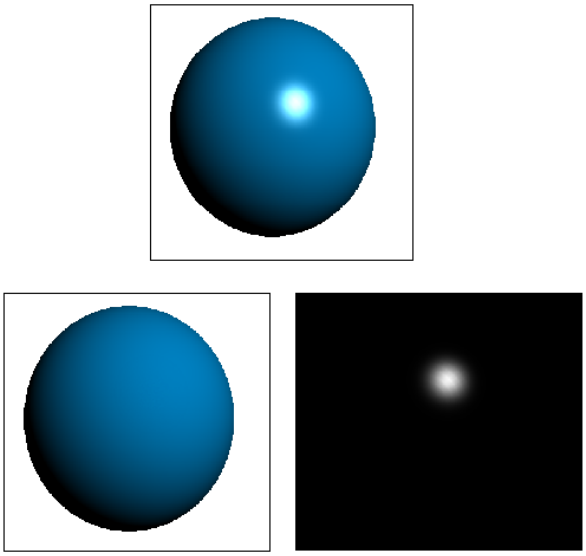


Figure 2. Original image and its diffuse and specular component image.

Horn and Brooks have in [Brooks and Horn 1989] proposed use of the unit normal rather then the gradient. This method is based on the minimization of $\int_{\Omega}(\mathbf{I}(\mathbf{x})\text{-}\mathbf{N}(\mathbf{x}).\mathbf{L})^2 \mathrm{d}\mathbf{x}$, where Ω is a region in XY-plane. In this paper is presented the iterative scheme where the surface normal is updated by taking a local average, and adjusting this either toward or away from the source.

4. TRANSFORMATION OF APPEARANCE

Our method requires two input images. First image is source image $\mathbf{I}_1(\mathbf{x})$. In this image object with the appearance of certain material is depicted. Second input image is object image $\mathbf{I}_2(\mathbf{x})$. This is target image of the object which appearance we would like to transform. The goal of this method is to change pixels of the object in target image $\mathbf{I}_2(\mathbf{x})$ to achieve the material appearance of the object depicted in source image $\mathbf{I}_1(\mathbf{x})$.

The color vector $\mathbf{p}(\mathbf{x})$ of the pixel of the object at the coordinates $\mathbf{x}$ can be described as follows:

$$\mathbf{p}(\mathbf{x}) = (\mathbf{N}(\mathbf{x}).\mathbf{L})\mathbf{d} + w_{\mathrm{i}}(\mathbf{x})\mathbf{s} \tag{6}$$

where $\mathbf{d}$ is the diffuse color coefficient and $\mathbf{s}$ is the illumination color which is (1,1,1) in this case. Let $\mathbf{H}$ is the bisector vector between the light and the viewing direction, $\mathrm{w}_{\mathrm{i}}(\mathbf{x})$ is the function of $\mathbf{N}(\mathbf{x}).\mathbf{H}$. First term in sum 6 represents the diffuse component of the pixel at the coordinates $\mathbf{x}$, second term represents the specular component. Applying the decomposition described in section 2 to both input images produces a specular component image and a diffuse component image for each of the input image. To estimate the geometry of both objects depicted in input images a shape from shading method is used. Results of proposed steps are captured in Figure 3.

To obtain surface normals, method described in [Brooks and Horn 1989] can be used. Let $\mathbf{N}_1(\mathbf{x})$ be the normal map of the object in the material image $\mathbf{I}_1(\mathbf{x})$ and $\mathbf{N}_2(\mathbf{x})$ be the normal map of the object image $\mathbf{I}_2(\mathbf{x})$. Let $\mathbf{x}_1$ be coordinates of the brightest pixel in the specular component image of the material image and $\mathbf{x}_2$ in the specular component of the object image. Let the bisector vector $\mathbf{H}_1$ is $\mathbf{N}_1(\mathbf{x}_1)$ and $\mathbf{H}_2$ be $\mathbf{N}_2(\mathbf{x}_2)$. Let $\mathbf{L}_1$ represents illumination direction in the material image and $\mathbf{L}_2$ in the object image. $\mathbf{L}_1$ is obtained as the reflection $2(\mathbf{E}.\mathbf{H}_1)\mathbf{H}_1$ - $\mathbf{E}$ and $\mathbf{L}_2$ as a reflection $2(\mathbf{E}.\mathbf{H}_2)\mathbf{H}_2$ - $\mathbf{E}$ where $\mathbf{E}$ is the vector (0,0,1).

Let $\mathbf{A}$ and $\mathbf{B}$ be tabular representations of a mapping from $\mathbb{R}$ to RGB space

$$A = \{(\mathbf{N}_1(\mathbf{x}).\mathbf{L}_1, d(\mathbf{I}_1(\mathbf{x}))) \mid \mathbf{x} \in \Omega_1\} \tag{7}$$

$$B = \{(\mathbf{N}_1(\mathbf{x}).\mathbf{H}_1, s(\mathbf{I}_1(\mathbf{x}))) \mid \mathbf{x} \in \Omega_1\} \tag{8}$$

where $\mathrm{d}(\mathbf{I}_1(\mathbf{x}))$ is diffuse component of $\mathbf{I}_1(\mathbf{x})$, $\mathrm{s}(\mathbf{I}_1(\mathbf{x}))$ is specular component of $\mathbf{I}_1(\mathbf{x})$ and Ω_1 is region in $\mathbf{I}_1(\mathbf{x})$. Data structure for $\mathbf{A}$ and $\mathbf{B}$ stores pairs of the dot product and the color and should be an binary search tree. For each pixel coordinates $\mathbf{x}$ of the object in the source image the dot product $\mathbf{N}_1(\mathbf{x})$. $\mathbf{L}_1$ and the color $\mathrm{d}(\mathbf{I}_1(\mathbf{x}))$ of the pixel at the coordinates $\mathbf{x}$ in the diffuse component of $\mathbf{I}_1(\mathbf{x})$ are stored into $\mathbf{A}$. Similarly, for each pixel coordinates $\mathbf{x}$ of the object in source image the dot product $\mathbf{N}_1(\mathbf{x}).\mathbf{H}_1$ and its corresponding specular component $\mathrm{s}(\mathbf{I}_1(\mathbf{x}))$ of the image $\mathbf{I}_1(\mathbf{x})$ are stored into $\mathbf{B}$.

Transport of the material appearance is achieved by changing color of pixels of the object in $\mathbf{I}_2(\mathbf{x})$. For each pixel coordinates $\mathbf{x}$ of the object in $\mathbf{I}_2(\mathbf{x})$ are certain colors $\mathbf{d}(\mathbf{x})$ and $\mathbf{s}(\mathbf{x})$ determined. From $\mathbf{A}$ are two elements (a_1,c_1) and (a_2,c_2) selected. The first element (a_1,c_1) where $a_1=\max\{a \mid a\leq\mathbf{N}_2(\mathbf{x}).\mathbf{L}_2,\ (a,c)\in A\}$ is the pair which has first component closest higher to $\mathbf{N}_2(\mathbf{x}).\mathbf{L}_2$, while the second element (a_2,c_2) where $a_2=\min\{a \mid a\geq\mathbf{N}_2(\mathbf{x}).\mathbf{L}_2,\ (a,c)\in A\}$ has its dot product component closest lower to $\mathbf{N}_2(\mathbf{x}).\mathbf{L}_2$. The color $\mathbf{d}(\mathbf{x})$ is then defined as the linear interpolation of the color components c_1 and c_2 of these two elements from $\mathbf{A}$. The color $\mathbf{s}(\mathbf{x})$ is defined as the linear interpolation of the color components c_3 and c_4 of two elements (b_1,c_3) and (b_2,c_4) from $\mathbf{B}$ where $b_1=\max\{b \mid b\leq\mathbf{N}_2(\mathbf{x}).\mathbf{H}_2,\ (b,c)\in B\}$ and $b_2=\min\{b \mid b\geq\mathbf{N}_2(\mathbf{x}).\mathbf{H}_2,\ (b,c)\in B\}$. Then the pixel color of each pixel of the object at coordinates $\mathbf{x}$ in the target image is changed as follows:

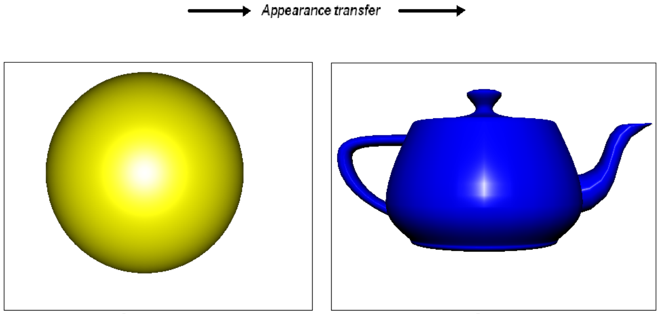
$$\mathbf{I}_2(\mathbf{x}) = \mathbf{d}(\mathbf{x}) + \mathbf{s}(\mathbf{x}) \tag{9}$$

5. RESULTS

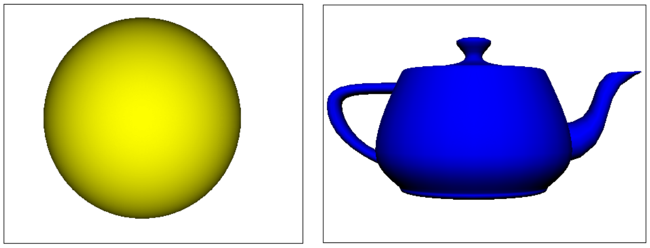
Proposed method was tested on multiple synthetic images using Phong and Cook-Torrance illumination model. Best results was obtained when in the source image $\mathbf{I}_1(\mathbf{x})$ was depicted single sphere with same light and viewer direction.

Figure 4 shows a material appearance transfer from the yellow sphere with the shininess coefficient 30 to the blue teapot with the shininess coefficient 100. The direction of the light in case of the sphere was (0,0,1) and estimation was $\mathbf{L}_1 =$ (-0.002,-0.001,1). In the case of the teapot the light direction was (0,-0.4,1) and the estimation of the light direction was $\mathbf{L}_2 =$ (-0.02,-0.18,0.983). Inaccuracies in normal estimations were affected by errors in the light direction estimations of the Zheng & Chellappa's method.

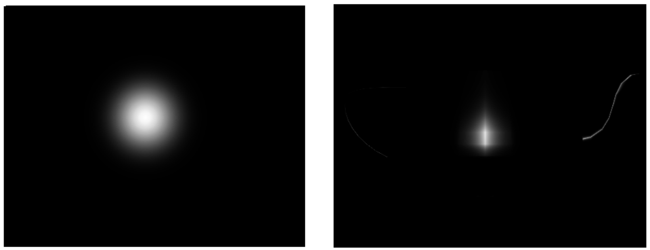
We evaluated mean square error according to formula 3 in diffuse transport to 0.038 and specular transport to 0.058. In Figure 5 are visualized differences in RGB space between result of this transfer and exact rendered image. In the upper part of teapot are some inaccuracies in specular component. In the diffuse component are inaccuracies at the boundaries caused by shape from shading algorithm.



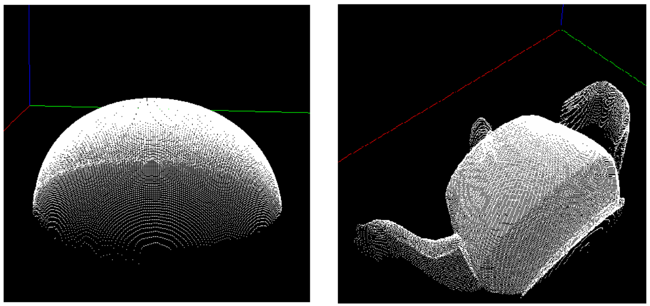
$\mathbf{I}_1(x)$ $\mathbf{I}_2(x)$



diffuse component of $\mathbf{I}_1(x)$ diffuse component of $\mathbf{I}_2(x)$



specular component of $\mathbf{I}_1(x)$ specular component of $\mathbf{I}_2(x)$



recovered shape of the object in $\mathbf{I}_1(x)$ recovered shape of the object in $\mathbf{I}_2(x)$

Figure 3. Steps required in the process of the transfer.

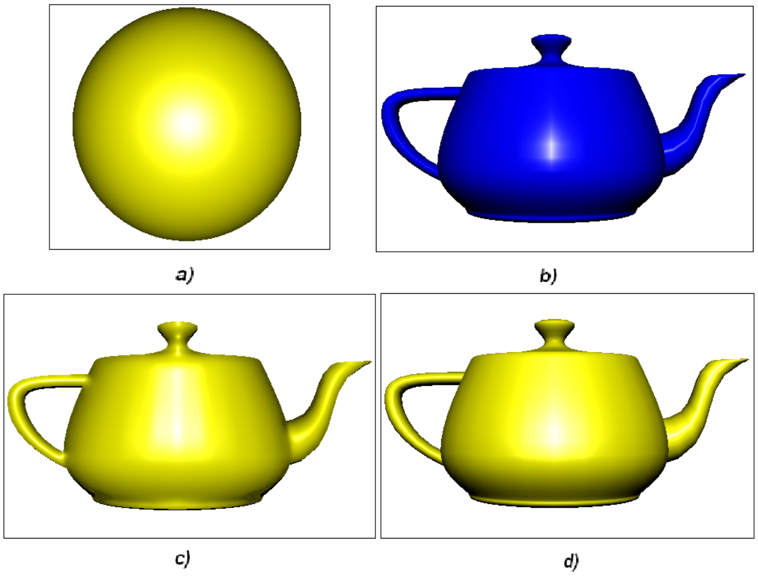


Figure 4. a) The source image $\mathbf{I}_1(\mathbf{x})$. b) The target image $\mathbf{I}_2(\mathbf{x})$. c) The material appearance of the object in $\mathbf{I}_1(\mathbf{x})$ transfered to the object in $\mathbf{I}_2(\mathbf{x})$. d) The original object from $\mathbf{I}_2(\mathbf{x})$ rendered with the same material parameters as the parameters of the object in $\mathbf{I}_1(\mathbf{x})$.

In the Figure 6 is shown result of the appearance transfer from the sphere with the metallic car painting to the yellow teapot. Estimation of $\mathbf{L}_1$ is (-0.16,-0.136,0.98) and $\mathbf{L}_2$ is (-0.0768,0.252,0.96). The Horn and Brooks algorithm tends to oversmooth the recovered normal map, which leads to losing of the boundaries. The problem of improper estimation of the geometry of the object in the material image $\mathbf{I}_1(\mathbf{x})$ leads to certain noise in the result. This noise is due to errors in the recovered normal map which leads to the constructions of structures $\mathbf{A}$ and $\mathbf{B}$ in which some element may have the dot product component higher then some others elements, but the color component consists of the color with lower intensity.

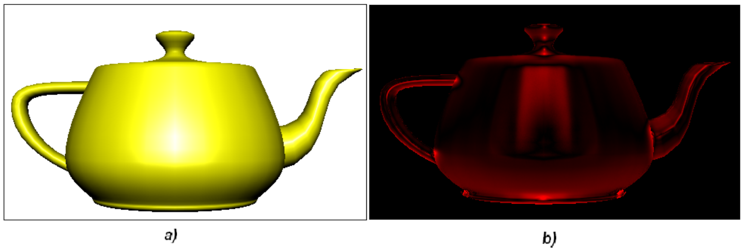


Figure 5. a) The exact rendered image. b) Inaccuracies of the result.

6. CONCLUSION

We have developed method which gets material of the object from single image and applies it to another image. The bottleneck of this method is the inaccuracy of the classic shape from shading algorithms. Despite not encouraging results of these approaches there can be some improvement accomplished by involving a user interaction to the shape recovering process as proposed in [Yasuyuki et al. 1999]. An attempt to decrease the dependency on the shape from shading algorithm of the proposed appearance transformation method may also increase the accuracy.

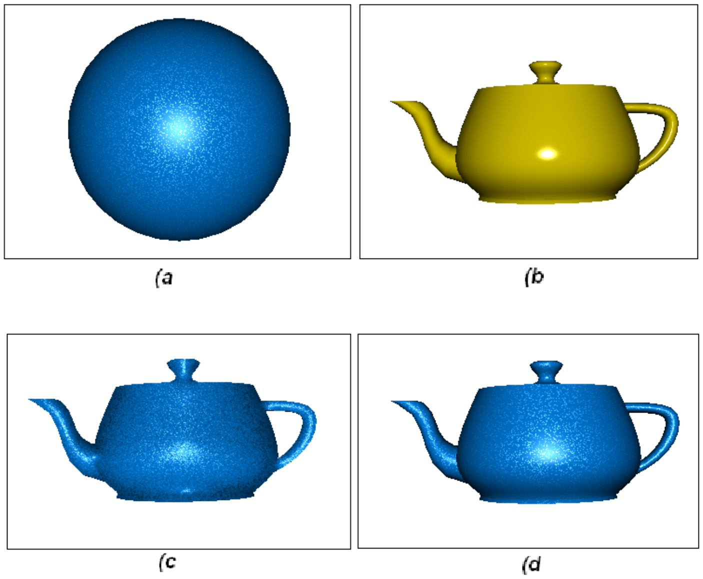


Figure 6. a) The source image $\mathbf{I}_1(\mathbf{x})$. b) The target image $\mathbf{I}_2(\mathbf{x})$. c) The material appearance of the object in $\mathbf{I}_1(\mathbf{x})$ transfered to the object in $\mathbf{I}_2(\mathbf{x})$. d) The original object from $\mathbf{I}_2(\mathbf{x})$ rendered with the same material parameters as the parameters of the object in $\mathbf{I}_1(\mathbf{x})$.

phong sphere diffuse decomposition	2.10^{-6}
phong sphere specular decomposition	10^{-5}
transfer from phong sphere to teapot	0.059
transfer from metalflek sphere to teapot	0.051

Table 1. Mean square errors.

Another improvement of the proposed method may be achieved by generalization of the assumption of the illumination and the object's surface composition. For example color changes in pearlescent paintings produces ambiguity errors in the process of the extraction of the diffuse component. Incorporating an environment map analysis may allow appearance transformation of the material surface which reflects surroundings.

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