Dense Estimation of Surface Reflectance Parameters from Registered Range and Color Images by Determining Illumination Conditions

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ABSTRACT

To reproduce a real object in CG, it is necessary to estimate reflectance properties of object surfaces. This paper describes a new method of densely estimating non-uniform surface reflectance properties of an object with convex and concave surfaces using registered range and surface color texture images obtained by a laser rangefinder. The proposed method determines positions of light to take color images for discriminating diffuse and specular reflection components of surface reflection. The Torrance-Sparrow model is employed to estimate reflectance parameters by using color images under multiple illumination conditions. Experiments show the usefulness of the proposed method.

Keywords: computer vision, image reconstraction, non-uniform reflectance modeling, illumination condition

1. INTRODUCTION

Image based rendering (IBR) methods often have been used to reproduce real objects in computer graphics (CG). Since a real image of an object is used as a texture of the object in IBR, a problem occurs, i.e., the appearance of the object is not reproduced appropriately when lighting conditions of real and CG environments are not consistent.

To overcome the problem, a number of methods of estimating reflectance properties of an object surface have been developed.[1–7] In these methods, reflection models with several parameters are employed and shape and color information of the object is used to estimate the reflectance parameters.

In some works,[1,2,6] it is assumed that an object has uniform reflectance properties over the entire surface. Reflectance parameters are estimated by using the standard least-squares method with a color image. Due to the assumption, these methods cannot be applied to objects which consist of several different materials and have non-uniform reflectance properties. To treat non-uniform surface objects, Kay and Caelli[3] have proposed a method which uses multiple images of an object under different lighting conditions and estimates reflectance parameters by solving simultaneous equations. However, the method still has a problem that results are not stable especially when the specular reflection component, which is one of the reflection component, is very small.

Recently, Sato et al.[7] have developed a methodology to estimate non-uniform reflectance properties. They set up an object on a robot arm and measure the object with a CCD camera and a rangefinder from many viewpoints by rotating the robot arm. In the method, reflectance parameters are stably acquired by decomposing the surface reflection into two components based on the singular value decomposition(SVD) technique. Although the method can be applied to objects with non-uniform reflectance properties, the shape of an object should be limited to convex. This is because it is difficult to observe the specular reflection component over the surface, since the lighting condition for a pose of the object against the camera cannot be changed in the method. Moreover, the difficulty of registration between range and color images may cause estimation errors.

We propose a new method for estimating non-uniform reflectance properties by observing the specular reflection component densely in the image obtained by a laser rangefinder which takes accurately registered range and color images of an object. In this paper, an algorithm is proposed to determine light positions with which the specular reflection component is strongly observed over the surface of a complex object even with convex and concave surfaces.

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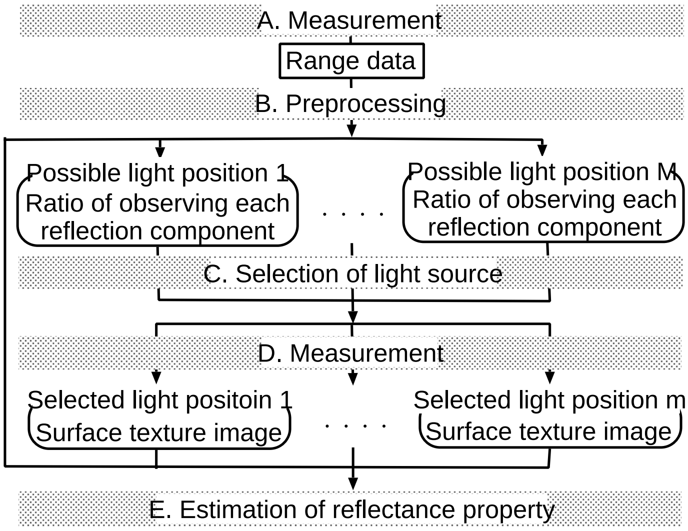


Figure 1. Flow diagram of estimating surface reflectance properties.

2. ESTIMATION OF REFLECTANCE PARAMETERS FROM RANGE AND COLOR IMAGES

2.1. Overview

In our method, the Torrance-Sparrow model is employed to estimate object surface reflectance properties from range and color images. Figure 1 shows a flow diagram of estimating surface reflectance properties. Our process consists of four parts, which are a measurement of an object (A, D), a preprocessing (B), a selection of light source (C), and an estimation of reflectance property (E).

2.2. The Torrance-Sparrow model

In this paper, the Torrance-Sparrow model,[8] which accurately represents object reflectance properties, is employed to estimate reflectance parameters. The Torrance-Sparrow model is given as:

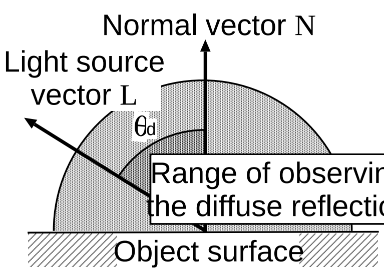
$$i = \frac{1}{C^2}(i_d + i_s), \tag{1}$$

$$i_d = P_d(\mathbf{N} \cdot \mathbf{L}), \tag{2}$$

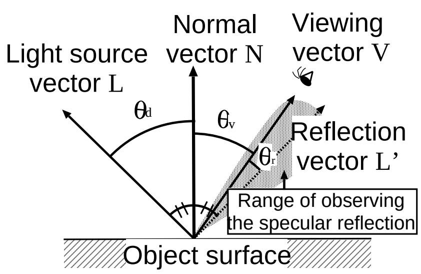
$$i_s = \frac{P_s}{(\mathbf{N} \cdot \mathbf{V})} exp(-\frac{(cos^{-1}(\mathbf{V} \cdot \mathbf{L}'))^{\mathbf{2}}}{2\sigma^2}), \tag{3}$$

$$\mathbf{L}' = 2(\mathbf{N} \cdot \mathbf{L})\mathbf{N} - \mathbf{L}, \tag{4}$$

where i represents an observed intensity, i_d and i_s denote the diffuse and specular reflection components, C is an attenuation efficient concerning the distance between a point light source and an object surface point, P_d is the



(a) Diffuse reflection



(b)Specular reflection

Figure 2. Diffuse and Specular reflection on an object surface.

diffuse reflectance parameter, P_s is the specular reflectance parameter, σ is the surface roughness parameter which is the standard deviation of a Gaussian distribution, $\mathbf{L}$ is a light source vector, $\mathbf{N}$ is a surface normal, $\mathbf{V}$ is a viewing vector, and $\mathbf{L}'$ is a reflection vector which is $\mathbf{L}$ mirrored against $\mathbf{N}$ and is given by Equation (4), respectively. All vectors are unit vectors. Figure 2 illustrates the geometry for this model.

In the case of using the color image, i, i_d, i_s, P_d and P_s consist of RGB channels and this model is applied to each channel. In order to estimate reflectance parameters P_d, P_s and σ with this model, it is necessary to obtain the other parameters i, C, $\mathbf{L}$, $\mathbf{V}$ and $\mathbf{N}$ at each point of the object surface.

2.3. Measurement of an object

To obtain unknown parameters other than reflectance parameters in the Torrance-Sparrow model, we use a laser rangefinder (Cyberware 3030RGB) with known positions of point light sources and a camera for acquiring surface color images, as shown in Figure 3(a). This system can obtain registered range and surface color texture images at a time by rotating the rangefinder and the camera around an object, so that there is no registration error, even when an object is measured many times. By using accurately registered multiple color images, reflectance parameters can be estimated accurately by solving simultaneous equations.

It is also important to observe the specular reflection component strongly to make calculations stable, since the specular reflection component is observed only within a limited range of angle around the reflection vector. Illumination conditions must be changed according to a measured object. To achieve this, multiple positions of a light are determined among many possible positions prepared around the laser rangefinder as shown in Figure 3(b).

2.4. Preprocessing

Generally, the noise is included in the range image acquired from the laser rangefinder. There is also a problem that the surface normal is not calculated accurately around the discontinuity in a range image. Therefore, we employ local quadratic surface fitting.

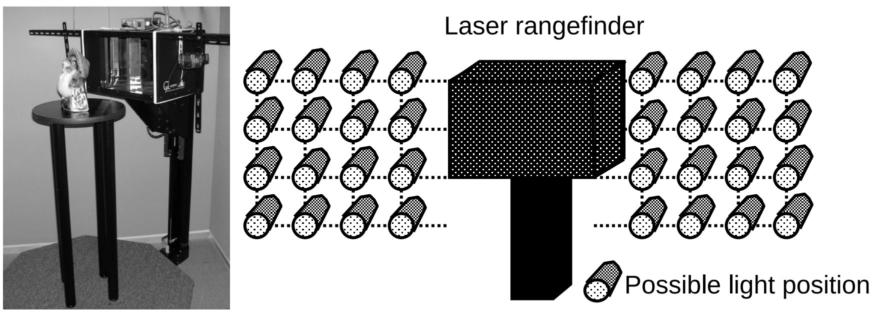
Firstly, 5×5 median filter is applied to the range image to remove the noise. Secondly, the quadratic surface is locally fitted with the range image. The range image is expressed by the cylindrical coordinates. Each point of the range image is shown as:

$$\begin{aligned}(x, y, z) &= \{-r(s,t)\sin(s), -t, -r(s,t)\cos(s)\} \\ &= \mathbf{S}(s,t), \end{aligned} \tag{5}$$

where r, s, t are the distance from the center of rotation, the angle of the rotation, the height along the rotation axis, respectively.

The unit normal vector is shown as:

$$\begin{aligned}\mathbf{N} &= \frac{\mathbf{S}_s \times \mathbf{S}_t}{||\mathbf{S}_s \times \mathbf{S}_t||} \\ &= \frac{1}{\sqrt{r_s^2 + r^2 + r^2 r_t^2}}\{-r_s\sin(s) - r\cos(s), \\ &\qquad -r_t r, \\ &\qquad -r_s\cos(s) + r\sin(s)\}, \end{aligned} \tag{6}$$



(a) Rangefinder (b) Possible positions of light source

Figure 3. System configuration for acquiring surface shape and color.

where r_s, r_t are gradient components of the range image $r(s,t)$. This gradient is computed using the following local surface fit:

$$
\begin{aligned}
r'(s,t) &= as^2 + bt^2 + cst + ds + et + f, & (7)\\
r'_s &= 2as + ct + d, & (8)\\
r'_t &= 2bt + cs + e. & (9)
\end{aligned}
$$

Coefficients $a \sim f$ are determined by minimising the following equation using the range data $r(s,t)$ and Equation (7).

$$
\begin{aligned}
error(s,t) &= \sum_{u=-2}^{2}\sum_{v=-2}^{2}\{r(s+u,t+v)\\
&\qquad -r'(s+u,t+v)\}^2, \qquad (10)
\end{aligned}
$$

where u, v are local coordinates in a 5×5 window. In our approach, selected local quadratic surface fit is achieved by using the Yokoya-Levine operator.[9] In this method, the best window is selected among 25 windows which include the point (s,t) to estimate coefficients $a \sim f$ at (s,t). The best window provides the minimum fitting error in Equation (10). Then, r'_s and r'_t are computed from Equation (8), (9) and the estimated coefficients $a \sim f$.

2.5. Selection of light source

To densely estimate non-uniform reflectance parameters independently, it is needed to observe the two reflection components separately for each pixel. However, since the diffuse reflection component is observed over the object surface, it is impossible to observe only the specular reflection component. The specular reflection component can be calculated by subtracting a value of a pixel which includes only the diffuse reflection component from that of the pixel which includes both the diffuse and specular reflection components. Therefore, it is needed to observe a pixel under three lighting conditions: one for observing only the diffuse reflection component to acquire one unknown parameter P_d based on Equation (2) and others for observing both the diffuse and specular reflection components to acquire two unknown parameters P_s and σ by solving simultaneous equations based on Equation (3). To observe every pixel under appropriate three different lighting conditions, the positions of the light are selected from M possible positions.

Let I_p be a color image which is to be obtained with a possible light position p ($p = 1, \cdots, M$) and consists of n pixels $(i_{p1}, \cdots, i_{pn})$, where i_{pk} means a color intensity, D_p be the number of pixels which include only the diffuse reflection component in I_p, and S_p be the number of pixels which include the specular reflection component strongly in I_p.

First, the following items are judged for each pixel in the object surface texture under each light position p.

- **Measurability of the light reflection**
- **Measurability of only the diffuse reflection**
- **Measurability of the strong specular reflection**

Second, the light positions p and q which satisfy $D_p = Max(D_1, \cdots, D_M)$ and $S_q = Max(S_1, \cdots, S_M)$ are selected. After the first light source selection is done, p and q are removed from each light source set. The next light sources are selected from the rest. Then, m light positions are selected to densely estimate reflectance parameters. The selections of positions are repeated until almost all pixels are observed once for only the diffuse reflection component and twice for the strong specular reflection component. We introduce a threshold th, i.e., the ratio of pixels that are observed to stop the process of selecting light positions.

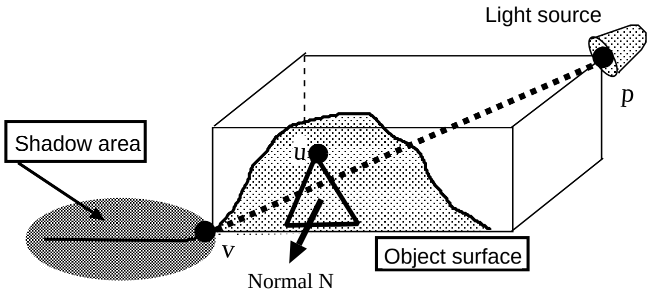


Figure 4. An illumination of detecting a self-shadow.

2.5.1. Measurability of the light reflection

In order to measure the light reflection at a specific point of the object surface, the point on the surface must be viewable from the camera. Additionally positional relationship among the camera, the point and the light source must satisfy the following conditions.

$$(\mathbf{V}_{pk} \cdot \mathbf{N}_{pk}) > \mathbf{0}, \ (\mathbf{L}_{pk} \cdot \mathbf{N}_{pk}) > \mathbf{0}, \tag{11}$$

where $\mathbf{V}_{pk}$, $\mathbf{L}_{pk}$, and $\mathbf{N}_{pk}$ are the viewing, the light source, and the normal vector at k-th pixel, respectively.

Even when the above equations are both satisfied, there is a possibility that a shadow is casted on the pixel. Figure 4 shows such a case. In this case, the pixel must not be used for estimating reflectance parameters. Whether a point v is covered by a shadow casted by light source p or not can be judged as follows.

Let $(x, y, z) = (v_x, v_y, v_z)$ be the coordinates of the point v on the object surface, $(x, y, z) = (p_x, p_y, p_z)$ be the coordinates of the possible light position. There is a bounding box which is surrounded by the maximum and minimum values on each xyz axis of position p and v as shown in Figure 4. Here, we can assume that all polygons which make the object surface are small enough to be covered by the bounding box. Then, in order to examine if a shadow is cast over v, we have to examine if any polygon that contains any vertex inside the bounding box intersects with the line segment that connects v and p. Therefore, for all point inside of the bounding box, the following test is performed.[10]

Let u be the point which is found to be included in the bounding box and $(x, y, z) = (u_x, u_y, u_z)$ be the coordinates of the point. If u lays on the plane whose normal vector is $\mathbf{N}$, the plane and the line segment which links p and v are given by the following equations, respectively.

$$\begin{cases} N_x(x - u_x) + N_y(y - u_y) + N_z(z - u_z) = 0, \\ t = \dfrac{x - v_x}{p_x - v_x} = \dfrac{y - v_y}{p_y - v_y} = \dfrac{z - v_z}{p_z - v_z}. \end{cases} \tag{12}$$

The intersection of the plane and the light segment, the point r can be obtained by solving Equation (12) about t. Now t is defined as follows.

$$\begin{aligned} t &= \frac{N_x(u_x - v_x) + N_y(u_y - v_y) + N_z(u_z - v_z)}{N_x(p_x - v_x) + N_y(p_y - v_y) + N_z(p_z - v_z)} \\ &= \frac{\mathbf{N} \cdot \mathbf{U}_v}{\mathbf{N} \cdot \mathbf{P}_v}, \end{aligned} \tag{13}$$

where $\mathbf{U}_v$ is the vector from the point u to the surface point v, $\mathbf{P}_v$ is the vector from the light position p to the surface point v. If t satisfies $0 \leq t \leq 1$ and the point r lays on the polygon which includes u, it is judged that the line segment of Equation (12) crosses the object.

2.5.2. Measurablility of the diffuse reflection only

When the k-th pixel consists of only the diffuse reflection, the reflection vector $\mathbf{L'}_{pk}$ satisfies the following equation.

$$\theta_r = cos^{-1}(\mathbf{V}_{pk} \cdot \mathbf{L}'_{pk}) > \theta_{th1}, \tag{14}$$

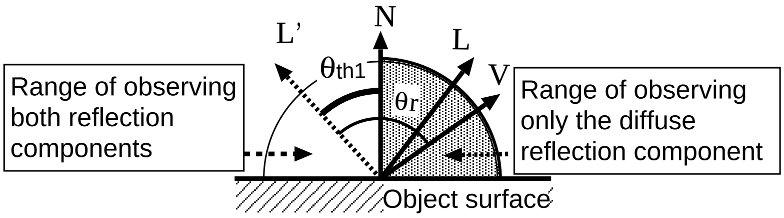


Figure 5. Observation of only the diffuse reflection component.

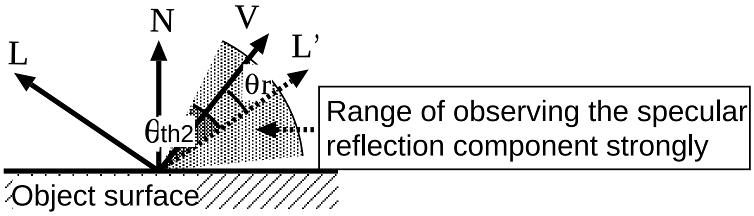


Figure 6. Observation of the specular reflection component strongly.

where θ_{th1} is a threshold angle between $\mathbf{V}_{pk}$ and $\mathbf{L}'_{pk}$. Equation (14) implies that only the diffuse reflection component is observed if θ_r is greater than θ_{th1} as illustrated in Figure 5. When this condition stands and the pixel is not in a shadow, the pixel is judged to have diffuse reflection only and is counted in D_p.

2.5.3. Measurability of the strong specular reflection

Since k-th pixel includes the specular reflection strongly, reflection vector $\mathbf{L'}_{pk}$ satisfies the following equation.

$$\theta_r = cos^{-1}(\mathbf{V}_{pk} \cdot \mathbf{L}'_{pk}) \leq \theta_{th2}, \tag{15}$$

where θ_{th2} is a threshold angle between $\mathbf{V}_{pk}$ and $\mathbf{L}'_{pk}$. Equation (15) means that both the diffuse and specular reflection components are observed if θ_r is smaller than θ_{th2} as illustrated in Figure 6. The above condition is based on the fact that the specular reflection is observed strongly in a limited range of a viewing angle. When this condition stands and the pixel is not in a shadow, the pixel is judged to have strong specular reflection and is counted in S_p.

2.6. Estimation of reflectance parameters

After the positions of the light source are determined, multiple color images are taken under the different lighting conditions and non-uniform reflectance parameters are estimated.

Let $I_{p,diff}$ be the set of pixels which consist of only the diffuse reflection component with possible light position p and consists of α pixels $(i_{p,diff,1}, \cdots, i_{p,diff,\alpha})$, where $i_{p,diff,k}$ means a color intensity. Let $I_{p,both}$ be the set of pixels which include the specular reflection component strongly, and consists of β pixels $(i_{p,both,1}, \cdots, i_{p,both,\beta})$, where $i_{p,both,k}$ means a color intensity.

2.6.1. Estimation of diffuse reflectance parameter

The diffuse reflectance parameter P_d is estimated by solving Equation (2) with the value of the k-th pixel $I_{p,diff,k}$ in the image $I_{p,diff}$, $\mathbf{N}_{pk}$ and $\mathbf{L}_{pk}$. In order to get the most reliable estimation, the pixel whose angle θ_r is the smallest but greater than θ_{th1} is selected.

2.6.2. Estimation of specular reflectance and surface roughness parameters

The specular reflectance parameter P_s and surface roughness parameter σ are estimated by solving Equation (3) with the value of the specular reflection component which is extracted from the k-th pixels $I_{p,both,k}$ and $I_{q,both,k}$ in the image $I_{p,both}$, $I_{q,both}$, $\mathbf{N}_{pk}$, $\mathbf{L}_{pk}$, and $\mathbf{V}_{pk}$. In order to get the most reliable estimation, the pixels whose angle θ_r are the smallest or the second smallest and are smaller than θ_{th2}, are selected.

First, the diffuse reflection component is computed with the estimated P_d and Equation (2). Second, the specular reflection component is extracted by subtracting the diffuse reflection component from Equation (1). Finally, specular reflectance and surface roughness parameters are obtained by solving the Equation (3).

It should be noted that Equation (3) can not be solved for a pixel at which strong specular reflection is observed less than twice. In such a case, the specular reflectance and surface roughness parameters are estimated by using a linear-interpolation method within a $W \times W$ window.

3. EXPERIMENTS

In our experiments, a measured object is a plastic doll and consists of non-uniform reflectance property as shown in Figure 7(a) and is assumed not to have interreflections. We fix some parameters as $\theta_{th1} = 60^o$, $\theta_{th2} = 20^o$, $th = 80\%$, $M = 60$ and $W = 3$. The proposed method of selecting positions of the light source determined seven light positions for the object.

Figure 7(b)$\sim$ (d) show the estimated reflectance parameters as the color intensity in the cylindrical coordinates. Figure 7(b) illustrates the diffuse reflectance parameter estimated all over the object surface. Figure 7(c) is the specular reflectance parameters. This image shows that the specular reflectance parameter of the doll's beak and leg are different from the rest. Actually, the beak and legs are highly reflective. This result corresponds with an observation of a doll in Figure 7(a). Figure 7(d) shows the surface roughness parameter with gray-scale where the largest value is white. This image means that the smaller the value is, the smoother the object surface is. Figure 7(e) shows the ratio of estimating specular reflectance and surface roughness parameters. The black part means that both parameters are not directly estimated. Non-uniform diffuse reflectance parameter for the whole observed object surface was judged to be estimated. Non-uniform specular reflectance and surface roughness parameters were judged to be estimated for 83% of the surface. There is a part where reflectance parameters cannot be estimated, because the normal vector is a vertical upward or downward. These parts are estimated by the linear interpolation.

Figure 8 shows rendered images using the parameters in Figure 7 with five different virtual light sources. The origin of the coordinate system locates at the object's barycenter, the positive direction of x, y and z axes agree with the right, upper and forward directions on the image plane, respectively. The viewing position locates at (0.0, 0.0, 20.0) and the viewing direction is toward negative direction of z axis. The virtual light source rotates around y axis. The position of the virtual light is shown as degree of the rotation. Let 0 degree be the front of the object. The width, height and depth of the object are 18.6 cm, 25.0 cm, and 14.8 cm, respectively. Note that the diffuse reflectance parameter represents the object's texture and the highlight is observed sharply at the doll's leg and beak under each illumination condition since this part has smooth material property.

Nevertheless, since the interreflection is not considered, doll's neck is not correctly estimated, where the observed intensity consists of secondary reflection from some object part. Moreover, because some part in the range image is blank with measuring by the laser rangefinder, the object is not rendered well.

4. CONCLUSIONS

In this paper, we have proposed a new method of densely estimating non-uniform reflectance properties for almost the whole object surface by using the laser rangefinder. For this purpose, multiple light source positions around the laser rangefinder are automatically selected, so that two reflection components are observed densely. The experiments have shown that the proposed method is useful for estimating the reflectance parameters. However since modeling a light includes some error and interreflections are not considered, reflectance parameters are not estimated stably in some part. In the future, we will improve the method so that a light is modeled accurately. We will also investigate a method to consider interreflections all over the object.

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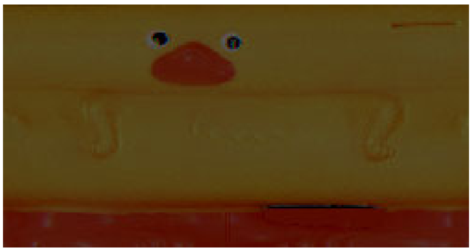
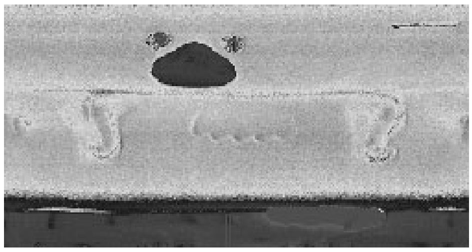
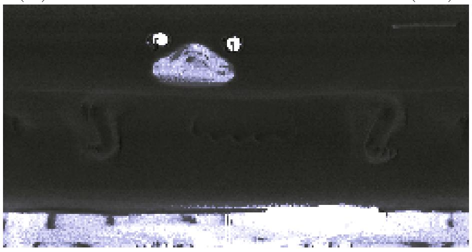
(a) Object



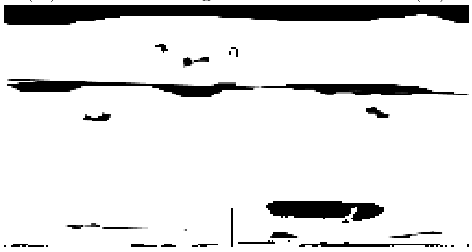
(b) Diffuse reflectance parameter (P_d)



(d) Surface roughness parameter (σ)

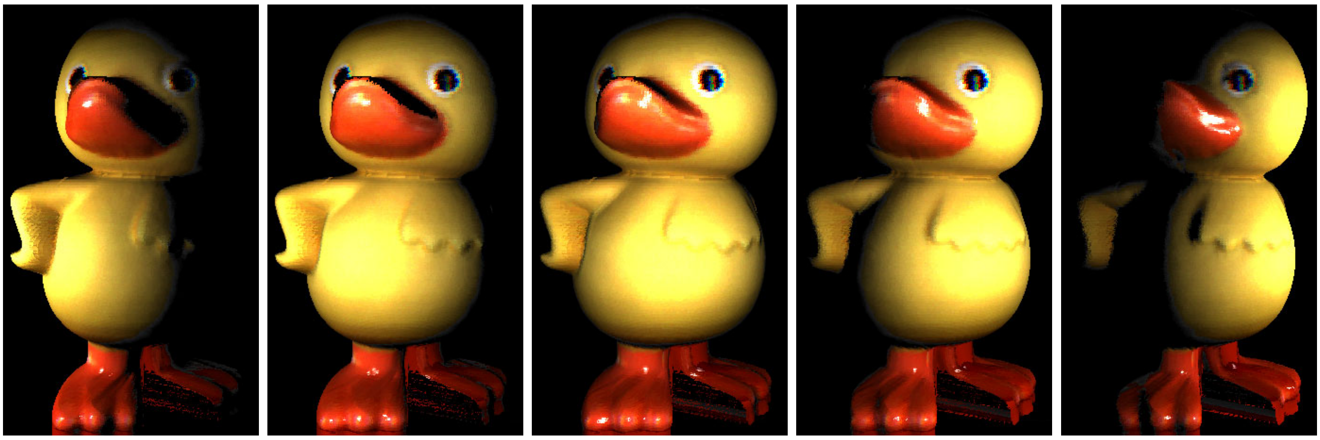


(c) Specular reflectance parameter (P_s)



(e) Area of specular reflection estimated

Figure 7. A measured object and estimated reflectance parameters.



(a) light 1 (-45.0^o) (b) light 2 (-22.5^o) (c) light 3 (0.0^o) (d) light 4 (22.5^o) (e)light 5 (45.0^o)

Figure 8. Rendering of object with virtual light sources.

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