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3D Free-Form Object Material Identification by Surface Reflection Analysis with a Time-of-Flight Range Sensor

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Abstract

The main objective in this research is to estimate 3D free-form real objects surface characteristics to identify the material based on surface reflectance analysis. To investigate the surface micro-structural detail, we use a time-of-flight range sensor to obtain the orientation of object local surface patches and the intensity of infrared scattering light reflected from those patches. A modified Torrence-Sparrow light reflection model is used to analyze the reflected infrared light. The surface roughness parameter, which represents the microstructure characteristics of object surface and can be an indicator of object material, is determined from the reflection model. We also have demonstrated the feasibility of the method through experiments. Since the original function of the sensor is to obtain 3D shapes of objects, we can develop an object recognition system with this sensor that can consider object material as well as shape.

1. Introduction

Development of various service robots recently attracts great attention. Such robots need vision systems to recognize objects necessary for carrying out their service tasks. However there still exist no conventional vision systems that can recognize target objects in the real world without fail. Interactive object recognition has been proposed for a practical solution to this problem. Robots ask their users to give helpful information to recognize the objects when they cannot recognize them. Kuno et al. presented an interactive object recognition system that can recognize objects through verbal interaction with the user on color and spatial relationships between objects [1]. Human users may provide material context to indicate objects such as, "Bring me that wooden box." Therefore vision systems need to obtain some corresponding material information to meet such requests. This paper proposes a method of recognizing object material by using a time-of-flight range sensor to be used in the interactive object recognition framework.

Several researchers have worked on this topic to identify object materials in noncontact manner by analyzing surface reflectance properties of the objects. Orun et al [2] have introduced a method that integrates the bundle adjustment technique to estimate local surface geometry and the laser surface interaction to examine the micro structure of material surface. In the experimental setup, they use two sources of laser light and a pair of CCD cameras. Due to these instrumental complexities and the need of their fine adjustment, the method becomes inappropriate to use in home environment to recognize household objects by service robots. Moreover, the 2W YAG laser light source used in the system is non-visible and harmful for human eyes. In the paper, they do not clarify the material color effect or visible light interference effect with the result. Tian et al [3] have proposed another active vision method, where a structured light based vision system is introduced to investigate surface roughness, defect, and waviness. The method also needs complex instrumental setup and tedious adjustment of illuminating condition. Culshaw et al. [4] have proposed an optical based measurement mechanism, which enables non-contact assessment of Poisson ratio and effective stiffness of object material. The method uses a laser-generated ultra-sound probe that produces lamb wave spectrum on the surface of the target object, which propagates through the surface and is detected by an interferometric optical detector. The system produces local heating on the small area of the object surface by the acoustic power generator, and the surface damage is very common. Thus, it is inappropriate for service robot applications. Recently, another method has been proposed in [5], to classify the material of real objects by investigating the degree of surface roughness. In this research the authors introduced a noncontact active vision technique by using a time-of-flight range sensor that has infrared light source to illuminate target objects. Although the method provides a promising result, it has a major limitation that it can work well only for some regular shaped objects. It cannot deal with complex shaped objects.

In this paper we propose a method that attempts to overcome the limitations as mentioned above. To investigate the surface characteristics we exploit both surface geometrical, micro structural information and its infrared light scattering pattern. We estimate the geometric properties of each point on the surface by fitting a quadratic surface on the local window centered at each point and then use differential geometry to calculate the orientation and curvature as well. The method has the capability to investigate the surface of any free-form real object of any color. After analyzing the reflectance properties against infrared light, the method classifies objects into several classes according to their surface roughness. The method is applicable for service robots at home environment. This is an active vision technique that uses infrared light as source. Since only the infrared light with certain band of frequency can reaches the sensor, the method can avoid interference from the visible light.

Another advantage that makes this method more suitable for robot applications is its simplicity. Our proposed scheme only needs a 3D range finder camera and nothing else. Since the time-of-flight range camera has already been used for localization, mapping and object shape recognition in robotics, our method can use the existing range finder camera to estimate the surface roughness. Hence in this robot vision application, it does not need any extra equipment.

2. Surface Reflection Model

The pattern of light reflected by a surface is highly dependent on the surface microscopic characteristic. Several researchers have worked to investigate the surface micro structural details by analyzing the reflected light. The Lambertian bidirectional reflection distribution function was used for modeling matte surface [6]. Phong reflection is an empirical model of surface illumination [7]. It describes the way that a surface reflects light as a combination of diffuse reflection with the specular reflection. The Torrance-Sparrow model describes surface roughness and is widely used in computer vision and graphic. The model is known as a useful tool for rendering realistic computer graphics images and synthesizing images. Moreover, the model aims to incorporate the effect of roughness into the specular reflectance component [8]. The calculation of reflectance is based on geometrical optics, and hence the model is applicable when the surface irregularity is comparatively larger than the wavelength of incident light. Nayar et al [9] showed that in such cases Torrance-Sparrow model approximates the Beckmann-Spizzichino [10] physical optics model. Shafer [11] and Tominaga [12] both used dichromatic reflection model for the spectral reflectance of the surface. Nayar et al [13] used a reflection model for matte surface that considers interreflection.

In our study, we use a modified form of Torrance-Sparrow model (1) to represent surface reflectance components. In this model we neglect the geometrical attenuation and Fresnel terms. Instead, we add the ambient term because there is a possibility of multiple reflections from other objects, walls and tables.

$$I = I_{in} \left\{ K_a + K_d \cos\theta_d + \frac{K_s}{\cos\theta_v} e^{\frac{-log(2)\times\Psi^2}{\gamma^2}} \right\} \quad (1)$$

where I_{in} is the strength of incident light, K_a, K_d, K_s and γ are the ambient reflectance, diffuse reflectance, specular reflectance and the surface roughness parameter, respectively. θ_d is the angle between the light source vector and the surface normal vector N, θ_v is the angle between the viewing vector and the surface normal vector, and Ψ is the angle between the half vector H and the surface normal vector as shown in Figure 1. A small value of γ indicates smooth surface and reflection from rough surface has a bigger γ value.

3. Principles of the Method

The amounts of light reflected by a surface, and how the light reflected, highly depend upon the degree of surface roughness. If the surface irregularity is much smaller than the wavelength of incident light as in the case of mirror or very smooth surface, virtually all of the light is reflected specularly to a specific direction. In the real world, however, most of the objects have convoluted surface and exhibit diffuse reflection as well as specular reflection. Hence, if we estimate the amount of diffuse part and the amount of specular part, we can predict the degree of surface roughness.

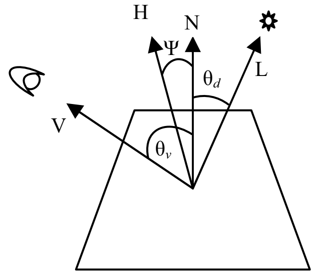

Figure 1. Reflection geometry.

However, the measurement of surface roughness by using visible light might be difficult in some cases. Since the size of micro-particles on the surface is almost equivalent to the wavelength of visible light, various types of matte or convoluted surfaces might have the same amount of specular and diffuse parts and we cannot obtain significant differences among various surfaces. If we use longer wavelength light, i.e., infrared light for illumination, we can enhance the discriminating feature between two surfaces. This is described in more detail in [5].

To project the infrared light on the surface of target object and to receive the reflection from the surface, we use a range imaging 3D camera, SwissRanger 4000 (SR4000) [14]. The SwissRanger 4000 is a solid state device that can measure the 3D position of each pixel as well as the intensity of the pixel. The camera has CCD array to produce an intensity image and is equipped with near infrared light sources. The device also has an optical filter in front of its CCD sensor panel to allow only near infrared light to reach the sensor. Visible light from other unwanted sources does not affect the CCD array output.

The received infrared light, reflected by a target object contains three components: specular component which is reflected by smooth surface part of the object, diffuse component which is reflected by matte part of the surface, and ambient component which is the gross approximation of multiple reflections from the wall, table and other objects in the scene. The ambient reflection produces a constant illumination on all surfaces, regardless of their orientation. It depends on the comparative smoothness or roughness of surface whether more light reflects specularly or diffusely. In this 3D imaging device, both image sensor and the light source are placed at the same position ($\theta_d = \theta_v = \Psi$ in (1)). Thus the sensor receives the maximum reflection from a surface if its orientation directs toward the sensor. If the surface orientation is getting away from this setting, the amount of total received reflection decreases. From this decreasing pattern, we can obtain the surface roughness parameter γ based on Eq. (1).

4. Technical Approach

To examine the reflection decreasing pattern, we need reflected intensity values I for various orientations θ_d. We compute the orientation of "surface patch" from the range sensor data as follows.

In our approach, we define "surface patch" as a small region on the surface. Each pixel on the surface surrounded by some other pixels constructs a patch. In order to estimate the geometric information of each patch, at first we fit a quadratic surface (2) to each patch and use the least square method to estimate the parameters of the quadratic surface. By using differential geometry, we calculate surface normal $\vec{n}$, angle between surface normal and viewing direction θ, Gaussian and mean curvatures K, H and principal curvatures $k_{1,2}$ [15][16].

$$f(x,y) = ax^2 + by^2 + cxy + dx + ey + f \tag{2}$$

$$\vec{n} = \frac{(-f_x, -f_y, 1)}{\sqrt{1 + f_x^2 + f_y^2}} \tag{3}$$

$$K = \frac{f_{xx}f_{yy} - f_{xy}^2}{\left(1 + f_x^2 + f_y^2\right)^2} \tag{4}$$

$$H = \frac{f_{xx} + f_{yy} + f_{xx}f_y^2 + f_{yy}f_x^2 - 2f_xf_yf_{xy}}{2\left(1 + f_x^2 + f_y^2\right)^{\frac{3}{2}}} \tag{5}$$

$$k_{1,2} = H \pm \sqrt{H^2 - K} \tag{6}$$

In our study, we consider only those surface patches that do not have large shape variation. The shape variation can be determined by the shape index. The shape index (SI) is a quantitative measurement of surface shape at a point. The shape index at any pixel position (i, j) is defined by (7) where k_1 and k_2 are the maximum and minimum principal curvatures, respectively. With this definition all shapes are mapped into the interval

$$SI(i,j) = \frac{1}{2} - \frac{1}{\pi} tan^{-1} \frac{k_1(i,j) + k_2(i,j)}{k_1(i,j) - k_2(i,j)} \tag{7}$$

0 to 1 [17]. Comparatively, convex surfaces have larger shape index values while concave surfaces smaller. Among them plane surfaces have medium shape index values. Therefore the shape index value represents the shape of a patch properly. From these values we select feature patches that are comparatively plane. The result of feature patch selection is shown in Figure 2 (magnified images), where the feature patches are marked by small squares.

In order to determine the patch orientation with respect to the viewing direction or illuminating direction, we calculate the angle δ between the patch normal and the viewing direction by (8). The viewing direction vector can be represented by the patch center vector $\overrightarrow{pc}$.

We compute the intensity value for each patch by averaging the intensity values of the pixels in the patch. The orientation and intensity data obtained are fitted to the modified Torrance-Sparrow model (1). Using the least square method we calculate the surface roughness parameter γ.

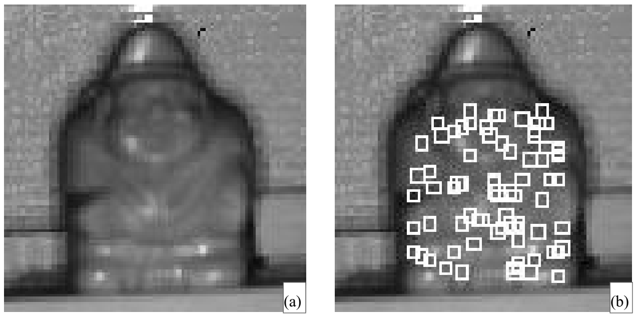

Figure 2. (a) Range image of wooden toy (b) showing its feature patches by white squares.

$$\delta = \frac{\cos^{-1}(\vec{n} \cdot \overrightarrow{pc})}{\frac{\pi}{180°}} \tag{8}$$

5. Experimental Result

We prepared nine objects that are made of seven different kinds of materials to perform experiments. The test objects included a white paper roll, a blue paper roll, and a white paper with complex shape to examine the effects of different colors and shapes.

Figure 3 shows the measurement results for white paper roll. Asterisk marks (*) indicate the measurement data for the surface patches and the curve shows the fitting result of the data to the model represented by Eq. (1). Figure 4 shows the fitted curves for all the objects.

We repeated the experiments five times for each object and computed the surface roughness parameter γ. Figure 5 shows the results.

The object samples or materials were not particularly selected according to the degree of roughness of their surface. Rather, they were selected among those which were commonly used in house. Some materials like ceramic and metal have more smooth surfaces than cloth and wood. On the other hand, some materials have comparatively moderate smoothness like the paper-made objects or the plastic cup. The experimental results indicate the order of roughness for these objects. They also show that object color and shape do not affect the measurement of roughness.

Note that the proposed method can be useful for interactive object recognition although it may not be able to identify object material. Human users may usually mention the material when there exist multiple objects of the same color or with the same kind of shape in the scene.

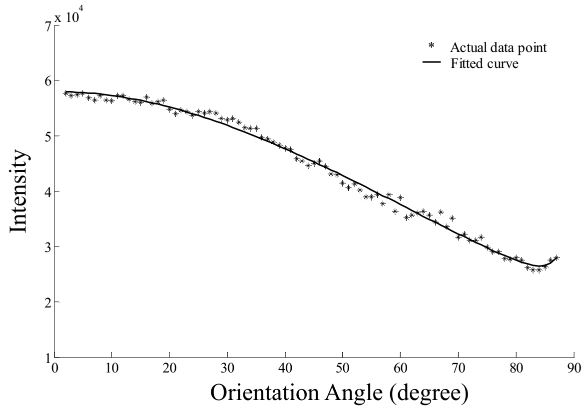

Figure 3. The measurement result for white paper roll.

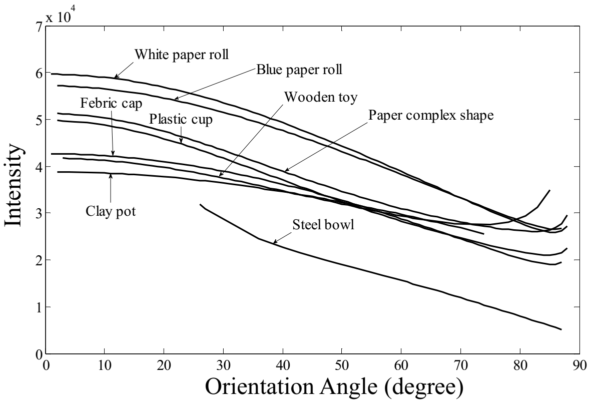

Figure 4. The measured reflection analysis data. Different surface types are represented by different curves.

The robot only needs to compare these objects, usually two or three, according to their surface roughness. It can be performed well as long as the relative order of roughness is discriminated. The experimental results show that the proposed method has the ability to provide such information.

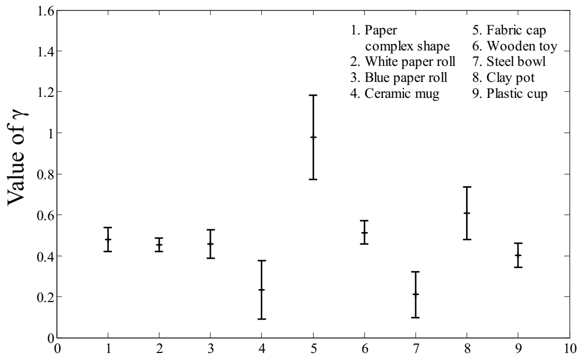

Figure 5. Result of 45 test cases of nine objects.

6. Conclusion

We have proposed a method for identifying object material by estimating the degree of surface roughness or smoothness using a time-of-flight range sensor. Surface roughness depends on the size of micro particles composing the material. We use a modified version of Torrance-Sparrow model for modeling light reflection. We have demonstrated the feasibility of the method by performing several experiments using nine common free-shape household objects made of seven materials. The range sensor can give surface orientation data. Since the original function of the sensor is to obtain 3D shapes of objects, we can develop an object recognition system with this sensor that can consider object material as well as shape. Human users may ask a robot, “Get that metal box,” or “Get that plastic box.” In this way our object recognition system can meet such requests. We are now developing such a robot vision system.

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References

[1] Y. Kuno, K. Sakata, and Y. Kobayashi: “Object Recognition in Service Robots: Conducting Verbal Interaction on Color and Spatial Relationship,” *Proc. IEEE 12th ICCV Workshops (Human-Computer Interaction)*, pp. 2025-2031, 2009.

[2] A. B. Orun, and A. Alkis: “Material Identification by Surface Reflection Analysis in Combination with Bundle Adjustment Technique,” *Pattern Recognition Letter,* vol. 24, issue 9-10, pp. 1589-1598, 2003.

[3] G. Y. Tian, R.S. Lu, and D. Gledhill: “Surface Measurement Using Active Vision and Light Scattering,” *Optics and Lasers in Eng.,* vol. 45, issue 1, pp. 131-139, 2007.

[4] B. Culshaw, G. Pierce, and Pan Jun: “Non-contact Measurment of the Mechanical Properties of Materials Using an All-optical Technique,” *IEEE Sensors Journal,* vol. 3, no. 1, pp. 62-70, 2003.

[5] M. Mannan, D. Das, Y. Kobayashi, and Y. Kuno: “Object Material Classification by Surface Reflection Analysis with a Time-of-Flight Range Sensor,” *Int. Symposium on Visual Computing,* vol. 6454, pp. 439-448, 2010.

[6] Edward Angel: “Interactive Computer Graphics: A Top-Down Approach Using OpenGL,” *Third Edition, Addison-Wesley,* 2003.

[7] B. T. Phong: “Illumination for Computer Generated Picture,” *Communication of the ACM,* vol. 18, no. 6, pp. 311-317, 1975.

[8] K. E. Torrance, and E. M. Sparrow: “Theory for Off-Specular Reflection from Roughened Surfaces,” *Journal Optical Society,* vol. 57, no. 9, pp. 1105-1112, 1967.

[9] S. K. Nayar, K. Ikenchi, and T. Kanade: “ Surface Reflection: Physical and Geometrical Perspective,” *IEEE Trans. Pattern Anal. Mach. Intell.,* vol. 13, no. 7, pp. 611-634, 1991.

[10] P. Beckmann, and A. Spizzichino: “The Scattering of Electro Magnetic Wave from Rough Surface” *Artech House, Inc., Nordwood, MA,* 1987.

[11] Steven A. Shafer: “Using Color to Separate Reflection Components,” *Color Research & Application,* vol. 10, no. 4, pp. 210-218, 1985.

[12] S. Tominaga: “Surface Identification Using the Dichromatic Reflection Model,” *IEEE Trans. Pattern Anal. Machine Intell.* vol. 13, no. 7, pp. 658-670, 1991.

[13] S. K. Nayar, and M. Oren: “Visual Appearance of Matte Surface,” *Science,* vol. 267, no. 5201, pp. 1153-1156, 1995.

[14] http://www.swissranger.com

[15] P. Flynn, and A. Jain: “On Reliable Curvature Estimation,” *Proc. IEEE Conf. Computer Vision and Pattern Recognition*, page 110-116, 1989.

[16] M. Suk, and S. M. Bhandarkar: “Three-Dimentional object recognition from range image,” *Springer-Verlag*, 1992.

[17] C. Dorai, and A. K. Jain: “COSMOS-A Representation Scheme for 3D Free-Form Object,” *IEEE Trans. Pattern Anal. Machine Intell.,* vol. 19, no. 10, pp. 1115-1130,1997.