Real-time Material Transformation using Single Frame Surface Orientation Imager

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Abstract: In this paper, we propose real-time reflectance transformation system using correlation image sensor and four LEDs. The reflectance transformation system changes object appearance into different materials one and displays it in the monitor. We have developed real-time surface orientation imager to add specular component according to captured normal vector map for reflectance transformation. Surface orientation of the object is encoded into amplitude and phase of the reflected light intensity by using phase shifted blinking LEDs, The correlation image sensor, provided by us, demodulates those amplitude and phase in each pixel during exposure time. Therefore, the surface orientation is captured by single frame, which can be applied to moving object. We developed reflectance transformation system using surface orientation captured by our real-time surface orientation imager. We demonstrated that the system provides relighting and changing reflectance property in real-time.

1 INTRODUCTION

Lighting and reflectance properties are important for material perception. Malzbender *et. al.* proposed reflectance transforming technique based on normal directions for enhancing surface detail(Malzbender et al., 2006). The system makes surface detail more apparent and amplify surface details, therefore it helps surface inspection. They proposed to enhance surface normal details by amplifying high-frequency variations in surface normals. Wenger *et. al.* proposed relighting and reflectance transformation system with time-multiplexed illumination especially for facial images (Wenger et al., 2005).

In this paper, we propose real-time reflectance transformation system, which is useful for visual effects (VFX) on entertainment system or television broadcasting program. The proposed system consists of four light sources and correlation image sensor(Ando and Kimachi, 2003). Modulated illumination encodes surface orientation into amplitude and phase of the reflected light intensity, and correlation image sensor demodulates those signals in each pixel at frame rate(KURIHARA et al., 2012),(Kurihara et al., 2003),(Kurihara et al., 2005). Based on reconstructed surface normals, we calculate intensity image under arbitrary illumination and reflectance parameters. Changing Lighting condition and reflectance transformation affect the reconstructed images immediately.

The following part of this paper describes the sensing and reflectance transformation principle we have developed using our 640×512-pixel correlation image sensor, and show experimental results of the reflectance transformation.

2 REAL-TIME SURFACE ORIENTATION IMAGER

2.1 Correlation Image Sensor(Ando and Kimachi, 2003)

The three-phase correlation image sensor (3PCIS) is the two dimensional imaging device, which outputs a time averaged intensity image $g_0(x,y)$ and a correlation image $g_\omega(x,y)$. The correlation image is the pixel wise temporal correlation over one frame time between the incident light intensity and three external electronic reference signals.

The photo of the 640×512 three-phase correlation image sensor is shown in Figure 1, and its pixel structure is shown in Figure 2.

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Let T be frame interval and $f(x,y,t)$ be instant brightness of the scene, we have intensity image $g_0(x,y)$ as

$$g_0(x,y) = \int_{-T/2}^{T/2} f(x,y,t)\,dt \tag{1}$$

Let the three reference signals be $v_k(t)$ $(k = 1,2,3)$ where $v_1(t)+v_2(t)+v_3(t) = 0$, the resulting correlation image is written like this equation.

$$c_k(x,y) = \int_{-T/2}^{T/2} f(x,y,t)\,v_k(t)\,dt \tag{2}$$

Here we have three reference signals with one constraint, so that there remains 2 DOF for the basis of the reference signal. We usually choose orthogonal sinusoidal wave pair $(\cos\omega t, \sin\omega t)$ as the basis, which means $v_1(t) = \cos\omega t, v_2(t) = \cos(\omega t + \frac{2}{3}\pi), v_3(t) = \cos(\omega t + \frac{4}{3}\pi)$.

Let the time-varying intensity in each pixel be

$$f(x,y,t) = A(x,y)\cos(\omega t + \phi(x,y)) + B(x,y,t). \tag{3}$$

Here $A(x,y)$ and $\phi(x,y)$ is the amplitude and phase of the frequency component ω, and $B(x,y,t)$ is the other frequency component of the intensity including DC component. Due to the orthogonality, $B(x,y,t)$ doesn't contribute in the outputs c_1,c_2,c_3. Therefore the amplitude and the phase of the frequency ω component can be calculated as follows(Ando and Kimachi, 2003)

$$A(x,y) = \frac{2\sqrt{3}}{3}\sqrt{(c_1-c_2)^2+(c_2-c_3)^2+(c_3-c_1)^2} \tag{4}$$

$$\phi(x,y) = \tan^{-1}\frac{\sqrt{3}(c_2-c_3)}{2c_1-c_2-c_3} \tag{5}$$

From the two basis of the reference signal $(\cos n\omega_0 t, \sin n\omega_0 t)$, we can rewrite amplitude and phase using complex equation.

$$g_\omega(x,y) = \int_{-T/2}^{T/2} f(x,y,t)e^{-j\omega t}dt \tag{6}$$

Figure 1: Photograph of Correlation Image Sensor(CIS).

Here $\omega = n\omega_0 = 2\pi n/T$. $g_\omega(x,y)$ is the complex form of the correlation image, and it is a temporal Fourier coefficient of the periodic input light intensity.

The advantages of the correlation image sensor are (1) single frame correlation detection, which enables real-time measurement, (2) suppression of noise which comes from enviromental illumination. So we adopt correlation image sensor to realize real-time surface orientation measurement in the uncontrolled environment.

2.2 Light Sources

To encode surface normal into amplitude and phase of reflected light intensity signal, we modulate four light sources at vertices of a square with the frequency ω, but those phase are different. The phase are set at those argument of each light sources in xy-plane. The values are shown in Table 1.

Consider the quadrature phase light sources $\mathrm{s_k}$ $(k = 0,1,2,3)$ of fig.3 which are arranged to make square, and the intensity is modulated by sinusoidal waves whose frequency is ω, and whose initial phase is $\frac{\pi}{4}, \frac{3\pi}{4}, \frac{5\pi}{4}, \frac{7\pi}{4}$. Therefore intensity of each light source is

$$S_k(t) = 1 + \cos\left(\omega t + \frac{(2k+1)\pi}{4}\right). \tag{7}$$

Let l_k $(k = 0,1,2,3)$ be the unit vector corresponding to the three light sources direction whose positions are $(L/2,L/2,H)$, $(-L/2,L/2,H)$, $(-L/2,-L/2,H)$, $(L/2,-L/2,H)$, respectively. Then l_k can be written as

$$\mathrm{l}_0 = \frac{(L/2,L/2,H)}{\sqrt{L^2/2+H^2}}, \qquad \mathrm{l}_1 = \frac{(-L/2,L/2,H)}{\sqrt{L^2/2+H^2}}, \tag{8}$$

$$\mathrm{l}_2 = \frac{(-L/2,-L/2,H)}{\sqrt{L^2/2+H^2}}, \qquad \mathrm{l}_3 = \frac{(L/2,-L/2,H)}{\sqrt{L^2/2+H^2}} \tag{9}$$

If the equation of an object surface is given explicitly as:

$$z = h(x,y) \tag{10}$$

then a surface normal is given by the vector:

$$\mathrm{n} = \frac{(-h_x(x,y),-h_y(x,y),1)}{\sqrt{1+h_x(x,y)^2+h_y(x,y)^2}} \tag{11}$$

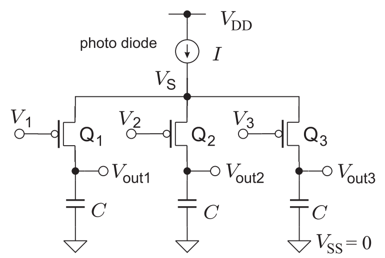


Figure 2: Pixel structure of the correlation image sensor.

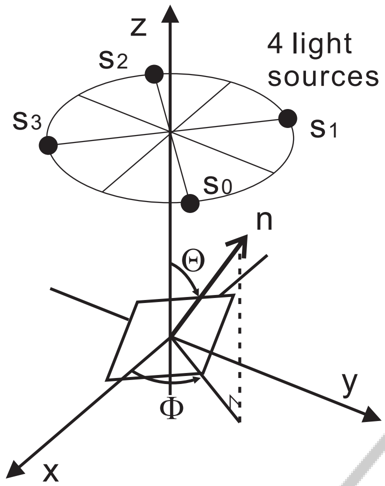


Figure 3: Geometry of quadrature phase light sources and surface normal.

Table 1: Position and initial phase of light sources

position	initial phase (deg)
$(\frac{L}{2}, \frac{L}{2}, H)$	45
$(-\frac{L}{2}, \frac{L}{2}, H)$	135
$(-\frac{L}{2}, -\frac{L}{2}, H)$	225
$(\frac{L}{2}, -\frac{L}{2}, H)$	315

where,

$$h_x(x,y) = \frac{\partial h(x,y)}{\partial x}, \qquad h_y(x,y) = \frac{\partial h(x,y)}{\partial y} \quad (12)$$

The object to be analyzed is assumed to have Lambertian reflectance and to be near origin so that the directions of four light from the whole surface is the same. Then, the brightness at the position (x,y) can be written as

$$I(x,y,t) = \sum_{k=0}^{3} AR(x,y)(\mathrm{l}_k \cdot \mathrm{n}(x,y)S_k(t) \quad (13)$$

$$= 4AR(x,y)\cos\psi\cos\Theta(x,y) + 2AR(x,y)\sin\psi\sin\Theta(x,y)\cos(\omega t + \Phi(x,y)) \quad (14)$$

where R denotes the surface reflectance index at (x,y), $\tan\psi = \frac{L}{\sqrt{2}H}$, and zenith angle and azimuth angle of the normal vector is Θ, Φ, respectively. Thus we can obtain the azimuth angle of the normal vector as the second term phase, and the zenith angle as the ratio between the first term and second term amplitude. Therefore, surface reflectance doesn't affect normal vector like photometric stereo method.

3 REFLECTANCE TRANSFORMATION

We obtain surface normal map by the method described in the previous section. Then we use these information for reflectance transformation. In this paper, we apply Blinn model to confirm real-time surface reflectance transformation principle,

$$I(x,y) = AR(x,y)(\mathrm{l}\cdot\mathrm{n}) + AS(\mathrm{h}\cdot\mathrm{n})^m \quad (15)$$

for arbitrary illumination direction l and normal vector n. Here h is a halfway vector between the viewer and light-source vectors v, l,

$$\mathrm{h} = \frac{\mathrm{v}+\mathrm{l}}{|\mathrm{v}+\mathrm{l}|} \quad (16)$$

4 SYSTEM

To show our principle, we have developed proto-type system consists of 4 IR(Infra Red) LEDs and correlation image sensor. The correlation image sensor has 640x512 resolution and it works at 15Hz and 30Hz. We used 15Hz frame rate. The illumination consists of Osram IR LED (SFH4750) whose wavelength is 850nm. The modulation frequency is set at 210 Hz, which means 14 times rotating during a single exposure. The distance between each LEDs is 500mm.

The computer captures correlation outputs through USB2.0 port from the correlation image sensor, and calculates surface orientation. Then the system outputs relighting images or the results of reflectance transformation on monitor.

5 EXPERIMENTS AND RESULTS

In the first experiment, we confirm the ability of the real-time surface orientation sensing. The target object is paper clay rabbit shown in Fig.5, which has diffuse reflectance property. Fig.6 shows captured images and reconstructed normal map.

Then we calculate reflectance transformation according to Blinn model. Fig.7 shows reconstructed intensity image for Blinn model $m = 15$. The rabbit in the reconstructed image seems to be made of china or to be covered somehow thin glass coating. So the material perception is quite different from original rabbit image.

In the next experiment, human face is used. Fig.8 shows captured images and reconstructed normal map. Strictly speaking, reflectance property of the

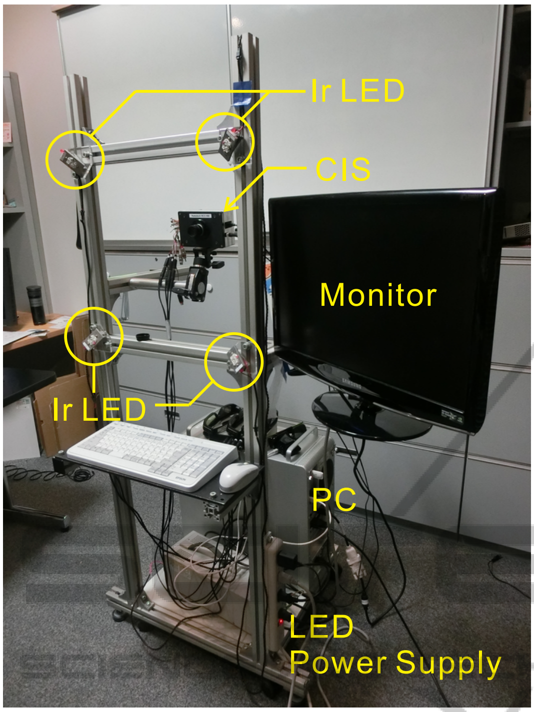


Figure 4: Photograph of real time surface orientation imaging system.

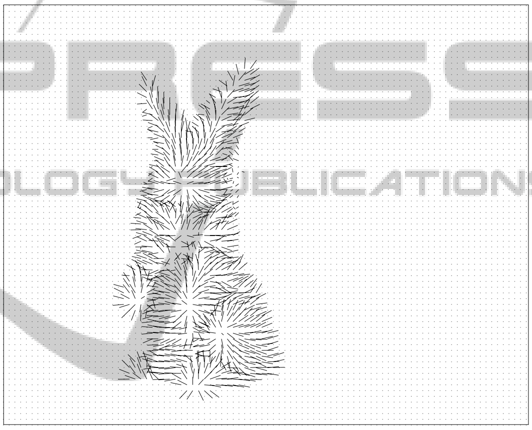
Figure 5: Target object: paper clay rabbit.

human face is different from Lambert reflectance, butthe reconstructed normal vector map shows its shape well.

Fig.9 show reconstructed results for different lighting conditions and reflectance parameters. These result make an impression that human face is made of china.

(a) Intensity image

(b) Correlation image



(c) Needle map

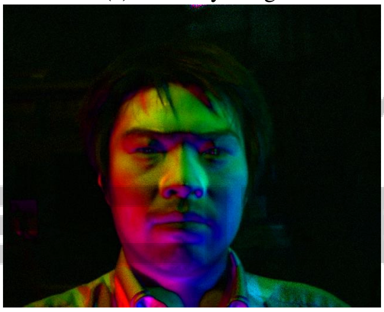
Figure 6: Captured images and reconstructed normal map.

(a)

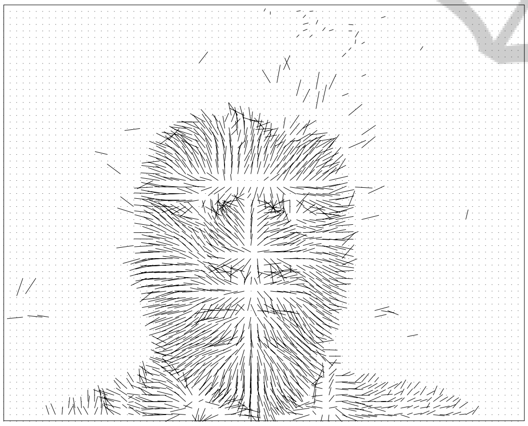
(b)

Figure 7: Relighting results for artificial specular reflectance of Blinn model for $m = 15$. (a)original reflectance property (diffuse), (b)Specular transformed object according to Blinn model.

(a) Intensity image



(b) Correlation image

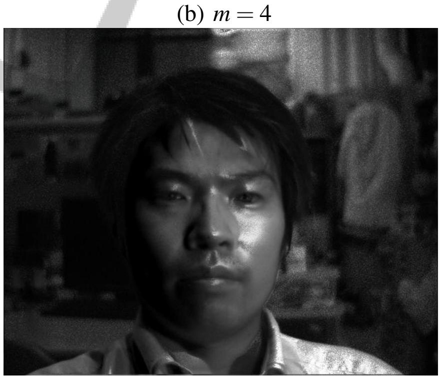


(c) Needle map

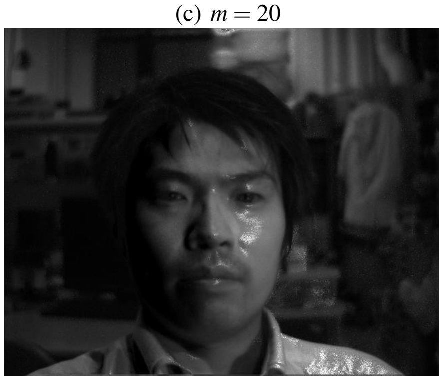
Figure 8: Captured images and reconstructed normal map.

(a) Diffuse

(b) $m = 4$



(c) $m = 20$



(d) $m = 100$

Figure 9: Relighting and reflectance transformation results. (a)-(d)Reflectance parameters were changed in the same lighting settings $(\theta, \phi) = (26^{\circ}, 0^{\circ})$.

6 CONCLUSIONS AND FUTURE WORKS

We have developed real-time reflectance transformation system using four light sources and correlation image sensor. Four light source and correlation image sensor enables real-time disturbance illumination free surface orientation imaging. Based on captured surface normals, reflectance transformation images are calculated and displayed on a monitor in real-time. This technique shows possibilities for an image expressing method in a television broadcasting or other media.

Based on the proposed system we will try further development for other material perception. Furthermore, we will apply projection mapping technique to transform material perception of real object. In other words, we are trying real-time real world VFX.

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