The Colloidal Metamorphosis

Time Division Multiplexing of the Reflectance State

Yoichi Ochiai ▪ *University of Tokyo*

Alexis Oyama ▪ *JiseCHI Future Imaging Lab*

Takayuki Hoshi ▪ *Nagoya Institute of Technology*

Jun Rekimoto ▪ *University of Tokyo*

A display system projects ultrasound waves to change the reflection state of a screen made of a colloidal substance—soap film. The system uses time division multiplexing of the diffuse and specular states to produce realistic appearances. It employs an optical illusion that exploits the characteristics of human sight.

Typical display screens are rigid and static, and they display the entire content in the same diffused manner. Furthermore, a screen's material can't be changed dynamically. However, in the real world, objects consist of different materials, with most materials having a distinguishing reflectance. It would be useful if a screen could reproduce a material's reflectance. We aim to achieve this by changing the screen's optical state.

When digital content is shown on a static surface, a significant amount of information is lost, including information regarding color, shape, depth, texture, and material. An object's appearance is determined mainly by its constituent materials' reflectance. If we could control this reflectance on the screen, we would no longer need to simulate certain materials by adjusting the brightness.

In a previous study, we used ultrasonic phased arrays to control the reflectance of a colloidal display made of soap film.[1] We've extended that research by determining how to reproduce a material's reflectance and evaluating the reproduced appearances. By alternating the soap film's reflectance at high speed through time division multiplexing, we can simulate different materials' reflectance, making the display more realistic. Figure 1 diagrams our system.

Theories

Here we describe the theory behind our colloidal display.

Capillary Waves on Soap Film

Diffusion on the ultrasound-activated colloidal film is caused by the capillary waves, which are dominated by surface tension. The dispersion relation of the waves on the display is

$$\lambda = \left(\frac{8\pi\sigma}{\rho f^2}\right)^{\frac{1}{3}},$$

where λ is the wavelength, σ is the surface tension, ρ is the colloidal solution's density, and f is the excitation frequency.[2] Suppose the colloidal liquid's surface tension is 1/2 of water (0.07275 N/m at 20 degrees C) and the density is the same as water (1,000 kg/m^3). With 40-kHz ultrasound, λ = 83 μm.

These minute waves (see Figure 2a) diffuse light. For simplicity, assume that the activated capillary wave is a sine wave. Figure 2b shows the relationship between the viewing angle and capillary wave. The capillary wave $g(x, t)$ is

$$g(x, t) = A\sin(kx - \omega t), \qquad (1)$$

where x is the distance along the x-axis; t is the time; A is the capillary-wave amplitude; k is the wave number, with $k = 2\pi/\lambda$; and ω is the angular frequency, with $\omega = 2\pi f$. When the incident light

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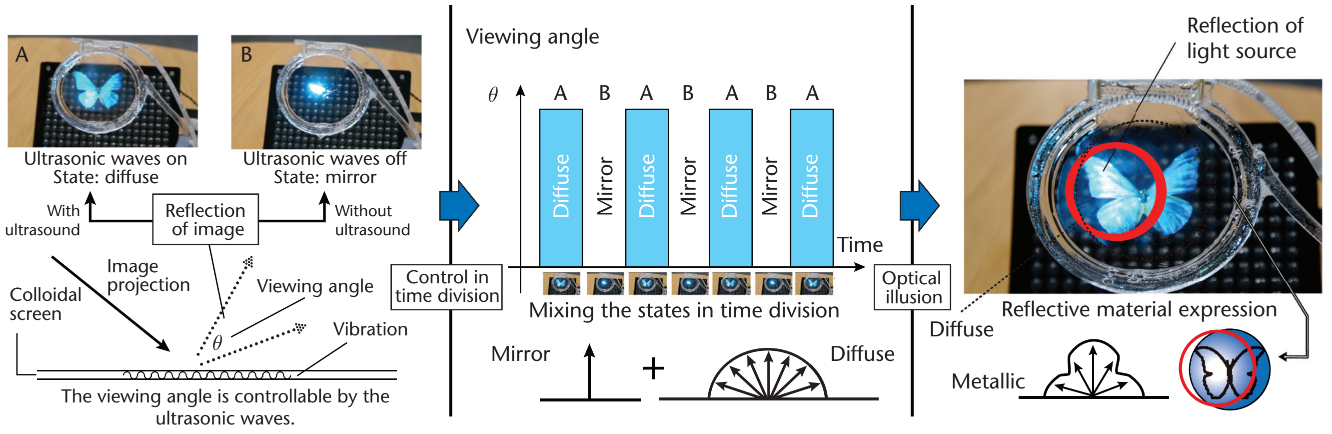

Figure 1. How our colloidal display works. At the left, the bold arrow represents the image from the projector. Applying ultrasound waves to the soap film changes the projected image's reflectance. When we apply the waves, the film bounces the projected image at an angle. We can control this viewing angle's range. In the figure, A denotes when the ultrasound is on, displaying the diffuse state, and B represents when the ultrasound is off, displaying the mirror (specular) state. By alternating these two states at high speed, the display presents an optical illusion that expresses different materials, such as metals.

is vertical to the colloidal film, from Equation 1, the reflection angle ϕ is

$$\phi = \operatorname{arccot}\left(\frac{-1}{Ak\cos(kx-\omega t)}\right).$$

Then, the colloidal display's viewing angle θ is 4ϕ. With our setup, the viewing angle is determined by A, which we assume is in proportion to the ultrasound's intensity.

Screen Reflection

The soap film's surface reflection is explained by the *bidirectional reflectance distribution function* (BRDF):

$$f_r(\omega_i,\omega_o) = \frac{dL_r(\omega_o)}{dE_r(\omega_i)} = \frac{dL_r(\omega_o)}{L_r(\omega_i)\cos\theta_i d\omega_i},$$

where r is the reflected light, ω_i is the incident light's direction, ω_o is the reflected light's direction, d is the differential, L is the radiance, and E is the irradiance. Furthermore, we can ignore the *bidirectional transmittance distribution function* by specifying the surface's state to obtain the BRDF only and to obtain a front projection. We ignore the radiation and absorption at the colloidal display.

A colloidal film doesn't have diffuse reflection characteristics; it's closer to a mirror. As with a mirror, the light emitted from the light source reaches the eyes in perspective (see Figure 3). So, the viewer sees only a dot or a light source on the mirror surface. We call this the mirror (specular) state.

We can project images on this surface by expanding the reflected light's viewing angle in the presence of ω_o in the BRDF model. In Figure 3, the expanded range of reflection for ω_{o1} is from ω_{o1}' to ω_{o1}''. The perspective light source that covers ω_o causes the image to appear on the film. We call this the diffuse state.

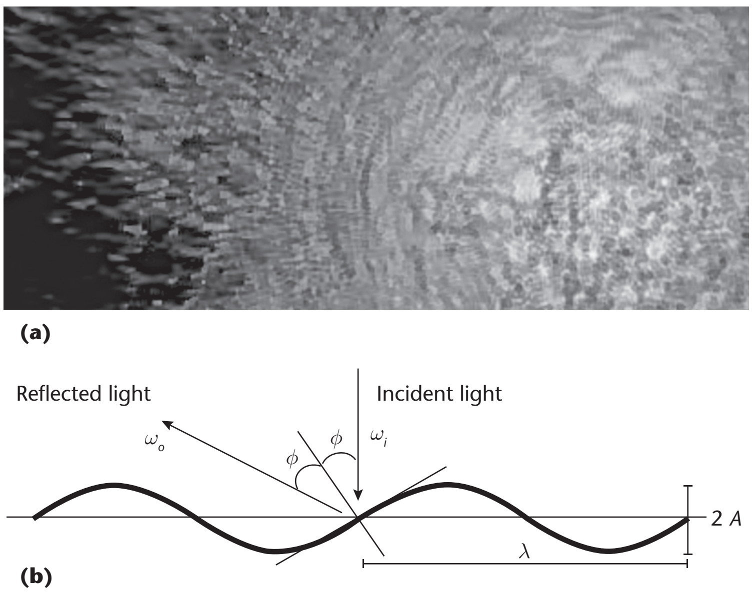

Figure 2. Diffusion on the ultrasound-activated colloidal film is caused by the capillary waves. (a) Capillary waves on soap film (200 × 500 pixels). (b) A simple model of the capillary waves. A is the wave amplitude, λ is the wavelength, and ϕ is the reflection angle.

We control the reflectance distribution on the basis of the theory we described in the previous section. On the basis of the principle of energy conservation, we express the relationship between L_r and L_i as

$$\int_{H_o^2} f_r(\omega_i,\omega_o)d\sigma^{\perp}(\omega_o) \le 1 \text{ for all } \omega_i \in H_i^2,$$

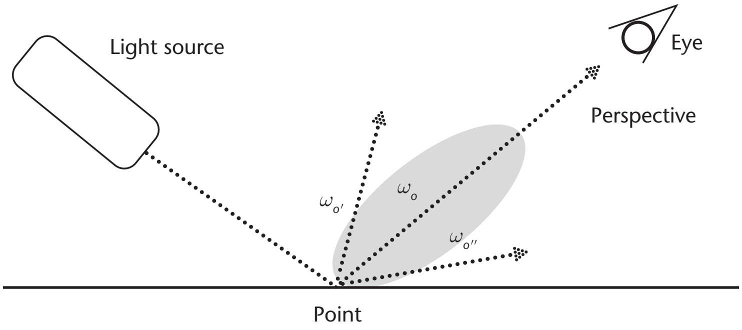

Figure 3. The relationship between the light source and the perspective. The angle from $\omega_{o'}$ to $\omega_{o''}$ is the viewing angle. The circle shows the irradiance.

where H means all directions in a hemisphere. We transform this to

$$\int_{H_o^2} dL_r(\omega_o) \leq L_i,\ \omega_o \in H_o^2.$$

This equation represents the tradeoff between the viewing angle and the projected image's brightness. This indicates that we can display an image with high brightness when ω_o is a narrow distribution.

The Ultrasonic Phased Array

We use phased-array focusing to vibrate the soap film within a localized area. We generate the ultrasound's focal point by setting adequate phase delays of multiple transducers. By controlling the delays, we can move the focal point to an arbitrary position. A tradeoff exists between the spatial resolution and array size as follows.

Theoretically, the spatial distribution of the ultrasound generated from a rectangular transducer array is shaped almost like a sinc function.[3] The main lobe's width (w) is parallel to a side of the rectangular array and is

$$w = \frac{2\lambda R}{D},$$

where λ is the wavelength, R is the focal length, and D is the length of the array's side. These parameters determine the resolution of ultrasound excitation of the colloidal display.

Alternating Reflectance

In the real world, the light emitted from the source reflects on an object's texture, resulting in our ability to simultaneously view both the object's reflection and texture. We aim to mimic this by using a projector as both the light source and image source. Traditional screens show only the image source; we can show both sources. The projector acts as a light source in the mirror state and as an image source in the diffuse state.

By quickly alternating between the two states, we can show an image with specific reflectance (see Figure 4). The transition time from the mirror state (ultrasound off) to the diffuse state (ultrasound on) is short and from the diffuse state to the mirror state is relatively long. This creates a difference between images displayed with different ultrasound frequencies, as we show later.

To control an image's brightness, we use multiple parameters: the projector's luminance, the image's brightness, the screen's reflection distribution, and the ratio of alternating the reflection states.

Hardware and Software Design

Compared to other BRDF displays, ours directly renders the image with less calculation. (For descriptions of two other BRDF displays, see the sidebar.) Moreover, we can determine the reflection parameters using two factors: the ratio of alternating the reflection states and the ultrasound intensity.

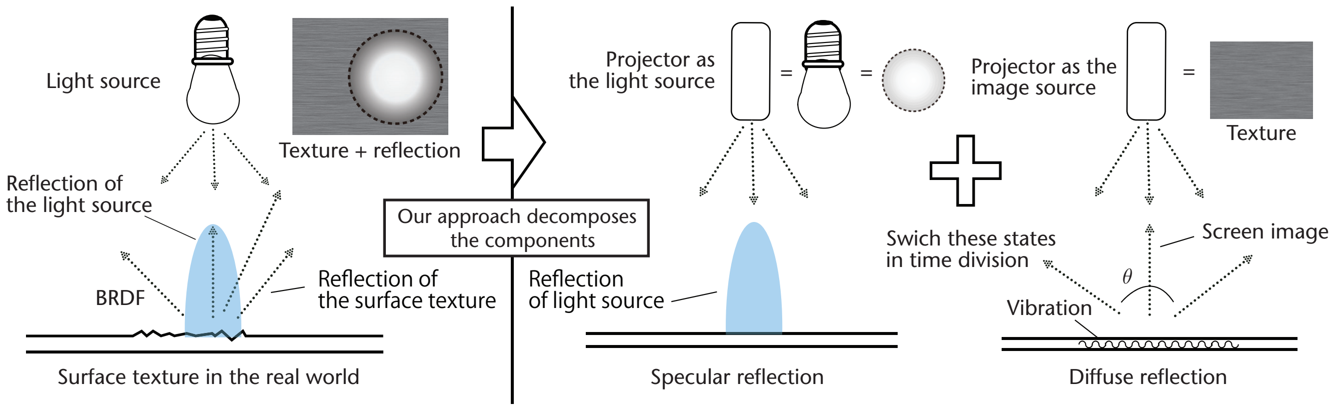

Figure 4. Mimicking a real-world texture by controlling the ratio of the mirror and diffuse states. BRDF stands for bidirectional reflectance distribution function.

System Requirements

The system must satisfy three requirements. First, the soap film must be light and sufficiently soft to change the optical properties using vibration. Second, the ultrasound device must operate at a high frequency. Finally, the system must supply the colloidal solution continuously to the display. This will extend the display's life by providing high stability against the powerful ultrasound waves.

System Overview

Our display comprises

- an LCD or Digital Light Processing projector;
- the colloidal film;
- the film's frame, with a waterfall system and a mechanism to replace the film; and
- the ultrasonic phased array.

Table 1 lists the parts' specifications.

Figure 5 shows a configuration of these components. The projector is in front of the colloidal display; its light falls on the soap film and the film's frame. We control the projected image from a PC. The ultrasound device is at a 45-degree angle to the soap film; its waves collide with the film, vibrating it. We control the device with our own software on Windows. The soap film has high surface tension and is flexible but is weak and fragile. If it breaks, servomotors replace it by soaking the frame in the soap solution.

Table 1. The colloidal-display components.

Component	Specification
Projector	LCD or Digital Light Processing
Display	
Colloid solution	Soap
Size	8-cm diameter
Ultrasound device	
Transducers	285 pieces
Focus control	Phased array
Frequency	40 kHz
Focal-point size	2 cm at 20 cm

Software Implementation

The software for controlling the ultrasound device was implemented in C. It enables us to switch

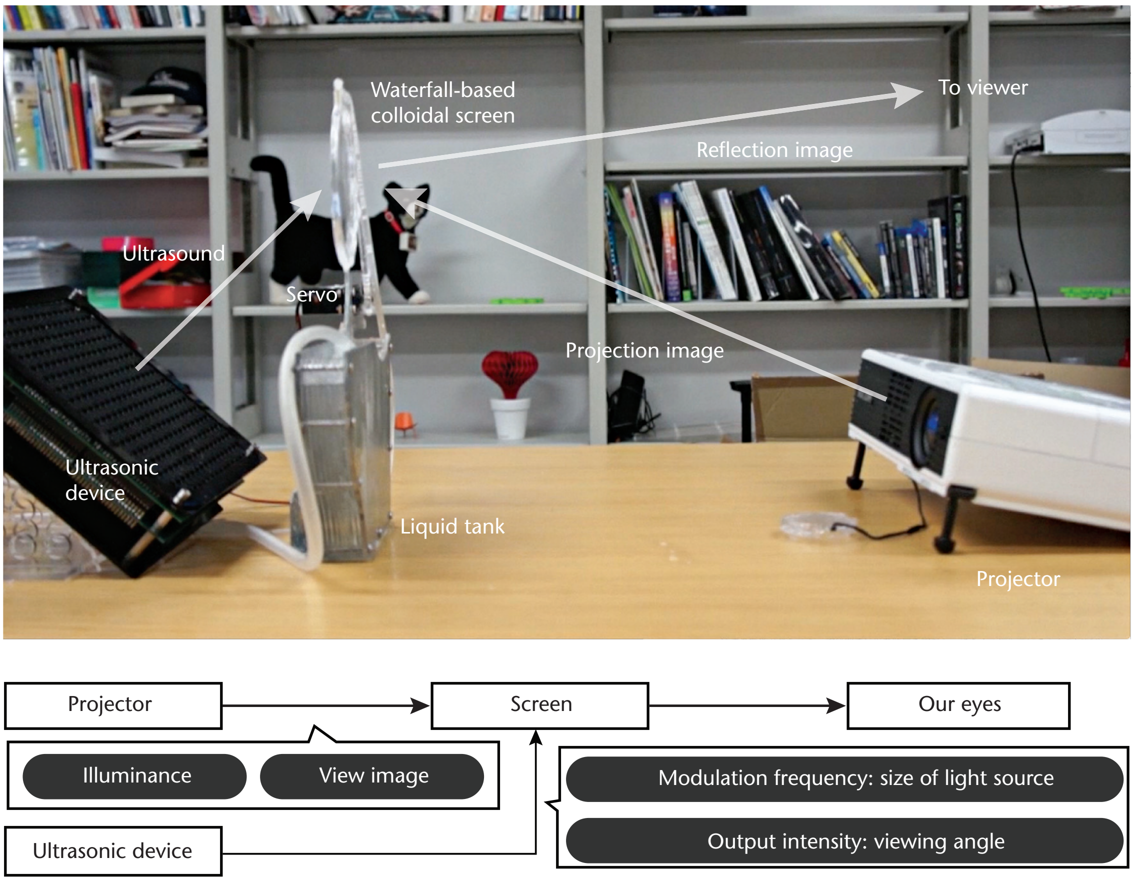

Figure 5. System components and controllable parameters for our colloidal display. As we switch the ultrasound waves on and off, we see the switch from transparent to opaque material.

Related Work in Displaying Textures

In the research described in the main article, we dynamically change the screen's texture by controlling the reflection over time. Here we look at other research on changing a virtual object's texture (reflection or surface shapes).

Displaying Textures

Studies on expressing textures[1,2] fall into two types:

- those employing a one-person view, using head-mounted displays or camera tracking,[3] or
- those employing a multiperson view, using a multiview display or controlling the screen's surface.

Because our approach controls the screen's reflection, it falls into the second category. So, here we look at research on multiperson-view systems.

Takafume Koike and Takeshi Naemura developed a *bidirectional reflectance distribution function* (BRDF) display.[4] To express an object's BRDF, they used a multiview LCD consisting of a lens array and integral photography. This method is computationally heavy, so it's not widely used for real-time applications and videos.

Researchers have developed several mechanical texture screens. Hayes Raffle and his colleagues' Super Cilia Skin employs an interactive surface with cilia-sized actuators that respond to magnetic force.[5] Marcello Coelho and Patti Maes's Sprout I/O uses actuators made of Teflon for the surface; these cilia-like structures bend and stretch.[6] In Masahiro Furukawa and his colleagues' Fur Display, a vibrating motor controls a surface of fur.[7] When the surface is activated, the hair stands up. The Fur Display supports user interaction with the fur by detecting the capacitance change. Like our display, these ones use actuation to express physical textures. This is good for wearable computing or interactive architecture, but the textures' expression range is restricted, and problems exist with the actuators' size and control.

Researchers have also realized dynamic texture displays by controlling microbumps on a display surface. Matthias Hullin and his colleagues' Dynamic BRDF Display changes the reflection parameter of its water surface through vibration.[8] This can diffuse reflection and blur the image. This display can express BRDFs that can't be expressed in an LCD display such as the one Koike and Naemura developed. However, this research has size limitations, and the display's orientation can't be changed. In addition, Yoichi Ochiai and his colleagues developed colloidal displays in which ultrasound waves control reflection.[9]

Finally, Yoichi Ochiai and Hiromu Takai developed a dot-matrix display that uses spinning black-and-white disks to create a flickering effect.[10] Changing the screen's reflection at a high frequency creates an optical illusion of a metallic appearance.

How Our Research Fits In

Although the Dynamic BRDF Display changes surface texture through detailed vibration, and the actuation's resolution is high, Hullin and his colleagues didn't focus on the projection. Studies on dynamic textures with small actuators haven't dealt with high resolution and have considered a limited variety of textures. In contrast, our research is particularly concerned with projection, and our display can reproduce a variety of textures, including those in some of the studies we just mentioned.

Figure A maps some of the research described in this sidebar; our research is marked in red. As Figure A1 shows, no other research covers the domain that ours does. As Figure A2 shows, our approach combines Ochiai and his colleagues' optical illusion, Ochiai and Takai's colloidal display, and the Dynamic BRDF Display's approach.

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the ultrasound's frequency and intensity. We set the ultrasound's focus at a long distance (63 cm) above the device to vibrate the whole surface of the film. We can control the switching frequency to a maximum of 1 kHz.

Controllable Parameters

The display lets us control three parameters related to texture appearance: reflection (through the viewing angle and timing), projection brightness, and the projected images.

We vary the screen's viewing angle by modulating the frequency of the ultrasound device's output intensity. The texture also changes the screen image's brightness when the projector's brightness and the digital image's brightness are given. If we change the image's contrast, the texture's appearance changes. This method is similar to the mix of image-based rendering techniques used in computer graphics.

Screen Images

Figure 6 shows the results for five viewing angles of four states:

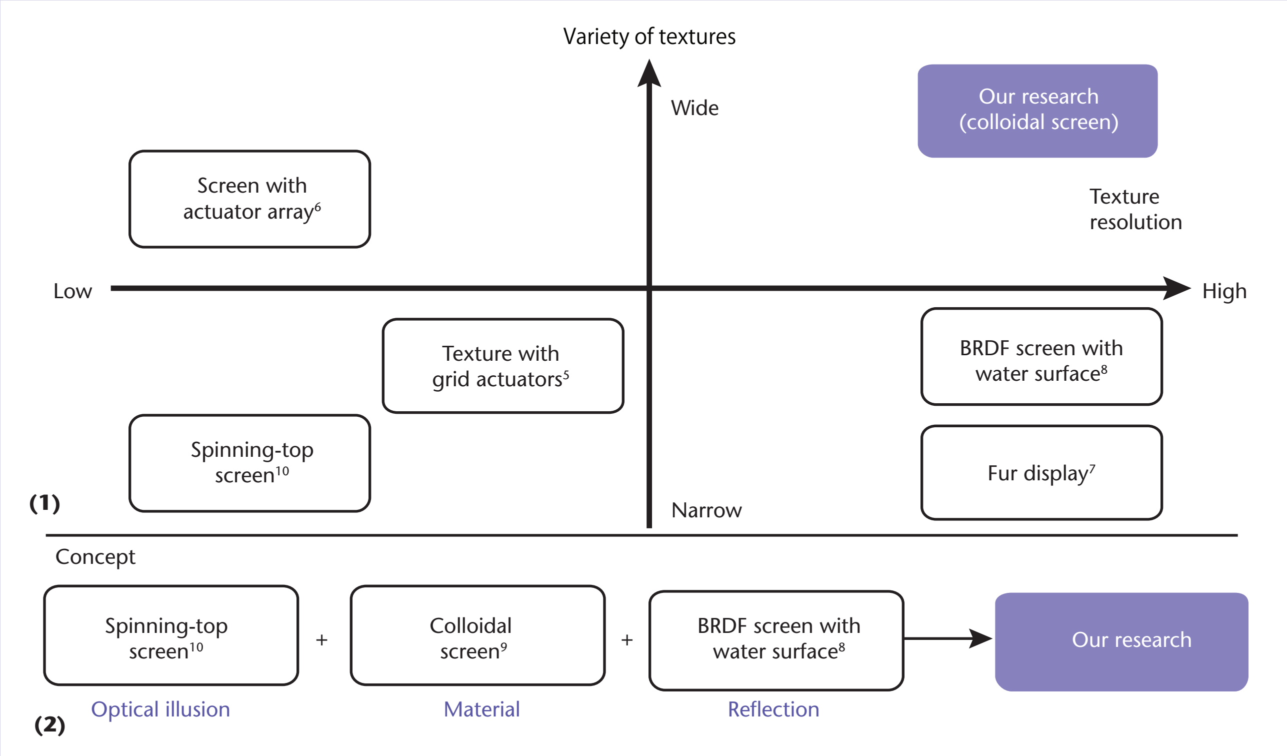

Figure A. Our research in context. (1) The research domain. (2) The research concept. BRDF stands for bidirectional reflectance distribution function. No other research covers the domain that ours does.

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- the mirror state,
- 20-Hz ultrasound modulation,
- 800-Hz ultrasound modulation, and
- the diffuse state.

With 20-Hz modulation, the display gleamed slightly. At 800 Hz, large bright spots moved with the viewing angle's change, appearing as a metallic luster. These spots show a different texture, which implies that we can change the appearance by changing the frequency while keeping the luminance value the same.

Evaluation

We conducted experiments to evaluate our display's reflectance, stability, and realism.

Screen Reflection

Figure 7 displays the results for different ultrasound intensities. Figure 7a indicates the relationship between the brightness and angle; Figure 7b shows the relationship between the viewing angle and ultrasound intensity.

The higher the ultrasound intensity is, the wider the viewing angle is. Considering the BRDF formula,

Figure 6. Sample results for four reflective states from five viewing angles. The red circle shows the reflective spot from the mirror state

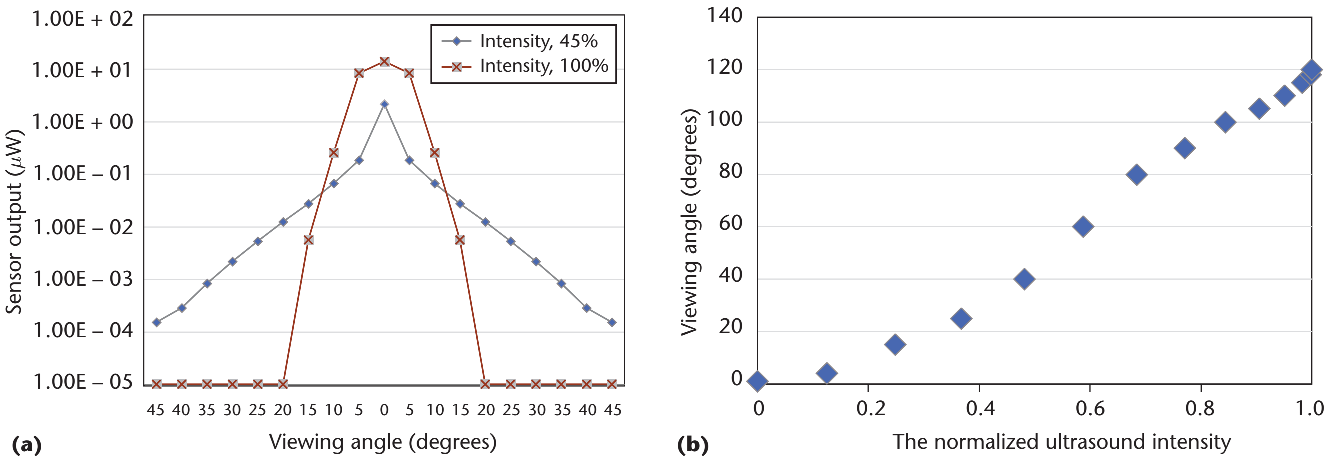

Figure 7. Evaluating screen reflection. (a) The relationship between the brightness and angle. The red line denotes a small viewing angle and is brighter than the blue line; the blue line denotes a wider viewing angle with low brightness. (b) The relationship between the viewing angle and the normalized ultrasound intensity.

we infer that such a change will change the distribution of the outgoing light ω_o. We can control this parameter's value from 0 to 120 degrees.

Screen Stability

On average, the soap film kept stable for 1 to 3 minutes, depending on the ultrasound intensity. The key factor is moisture; the image will be noisy when the film contains less water. As time passes, the water evaporates, deteriorating the transmission characteristics and disturbing the image. The main reason for this disturbance is the failure to control the reflection.

Laser Tests on Our Display

We set the incident at an angle of 45 degrees from the display and examined the laser reflection intensity patterns. We used a 1-watt blue laser and set 10 photodetectors at 5-degree intervals. When the viewing angle increased, the brightness decreased.

Figures 8a, 8b, and 8c illustrate how the brightness changed with the modulation frequency. The graphs show the average values of the samples. The sampling rate was 50 Hz.

Human Tests

Study participants viewed an image on an LCD

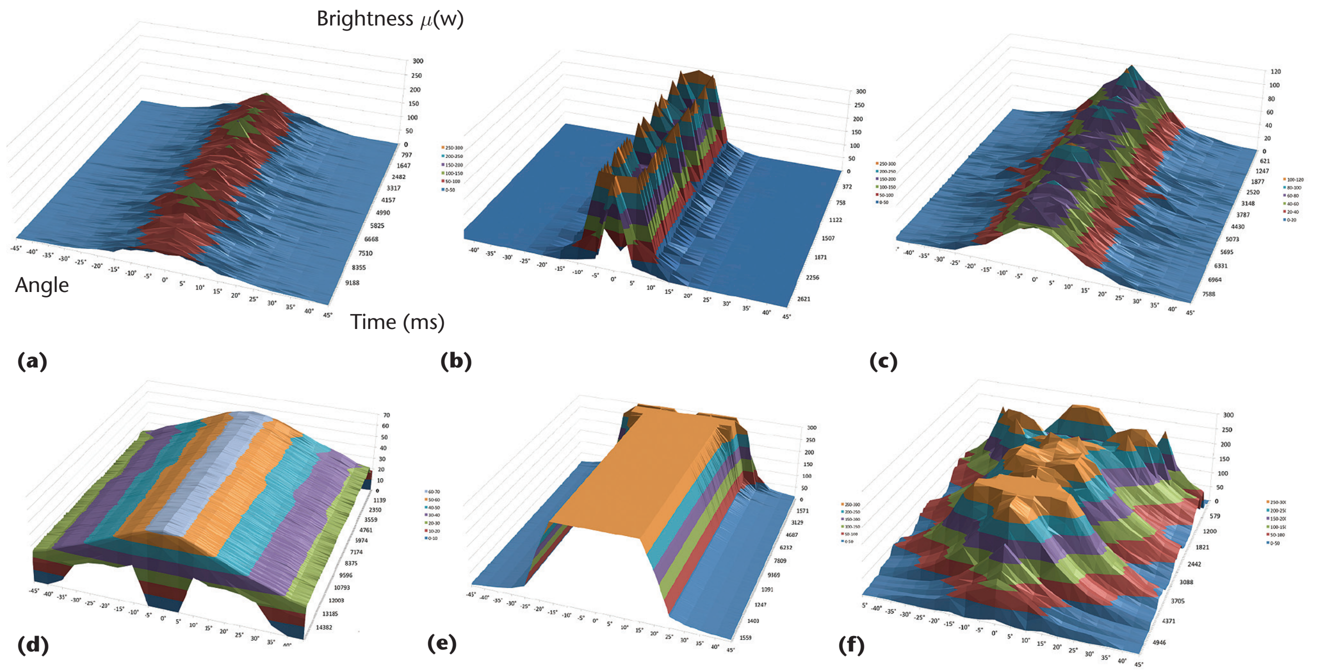

Figure 8. How brightness changed with modulation frequency, for tests with a laser. (a) Diffuse reflection on our display. (b) The reflection with 60-Hz modulation on our display. (c) The reflection with 400-Hz modulation on our display. (d) Diffuse reflection of regular paper. (e) The reflection of aluminum sheet A in Figure 9. (f) The reflection of aluminum sheet B in Figure 9. The graphs for sheet A and 60-Hz modulation are similar, and those for sheet B and 400-Hz modulation are similar. This proves our display can show images resembling real material.

screen and an image on our display and indicated which looked more like the real material, which in this case was aluminum foil. Most participants found our display's image to be more realistic.

Then, we showed the participants two sheets of aluminum foil; sheet A had the shiny side visible, and sheet B had the dull side visible (see Figure 9a). We asked them to select which one of several images projected on our display was most like each sheet. The participants stated that 20- or 60-Hz modulation looked more like sheet A and that 400-Hz modulation or the diffuse state looked more like sheet B.

Further Laser Tests

For comparison, we performed a laser test on regular paper to illustrate diffuse reflection (see Figure 8d). We then performed laser tests on sheets A and B; Figures 8e and 8f show the brightness graphs. As you can see, the results for sheet A were similar to those for 60-Hz modulation, and the results for sheet B were similar to those for 400-Hz modulation and the diffuse state. Moreover, the laser reflection images for our display resembled those for the real material (see Figure 9b).

This implies that the intensity of the reflection pattern in the brightness graphs for our display is similar to that of the real material and that our results are therefore considerably realistic.

Discussion

Here we examine our display's limitations and potential uses.

Soap Film Limitations

The soap film's durability depends on the ultrasound device's power and the soap itself. Furthermore, a small disturbance such as a breeze or humidity change will affect it. We can increase the soap film's life span by using a pump that continuously provides the soap solution to the frame. We also found a glue-like substance that helps the film last more than a day.

Optical-Property Limitations

When turning transparent soap film into an opaque display, we found that certain spots can't be covered and remain transparent. The coverage area is roughly 95 percent. Typically, the outer rim is transparent because the frame blocks the ultrasound waves.

Practical Use of the Display

One practical use of this technology is to obtain a dynamic reflection reference for materials (for example, dynamic sampling of printing, furniture, metal, and fabric). This is useful for people choosing materials for products. Moreover, employing this technology to parameterize an

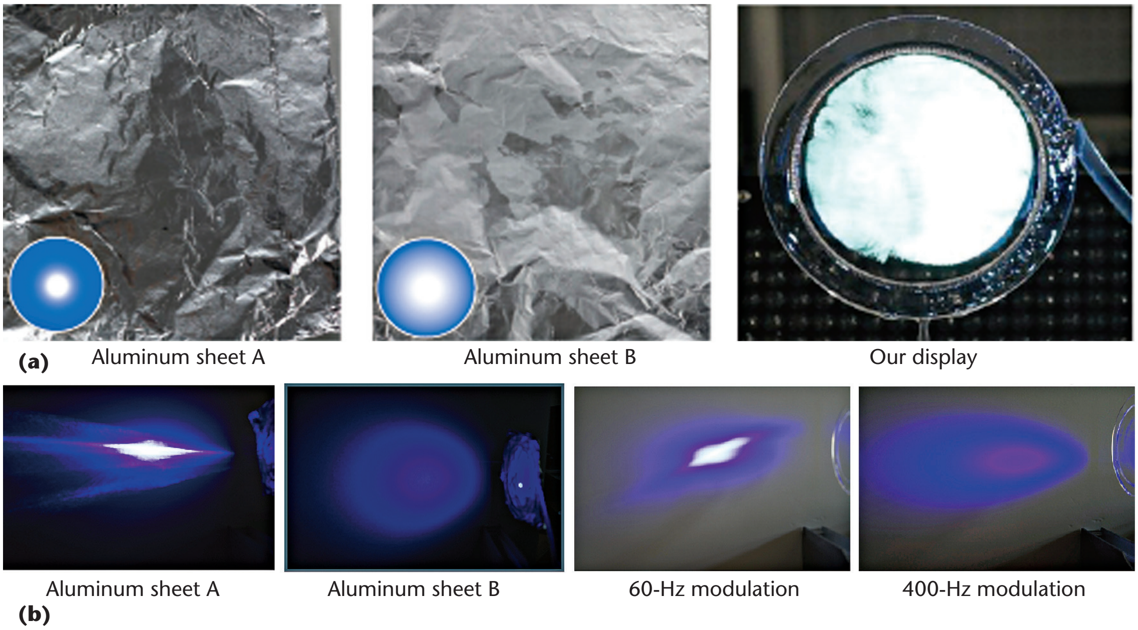

Figure 9. Comparing our display to two sheets of aluminum foil. (a) The two sheets and an aluminum-like image on our display. Sheet A had the shiny side visible; sheet B had the dull side visible. The insets in the first two images illustrate the size of reflection spots. (b) Laser reflection on the two sheets and on our display at 60- and 400-Hz modulation. Note the similarities between sheet A and 60-Hz modulation and between sheet B and 400-Hz modulation.

object's reflectance is useful for people who want to design a product's appearance, predict the appearance of coatings, or discuss appearance in a consistent way.

In multimedia, it's important to show digital content that's as realistic as possible. Our system contributes to this goal by controlling reflectance in real time. However, properties other than reflectance are also important. Examples include an image's color and smoothness (that is, the projected image might be pixelated). We're investigating how to show the *bidirectional surface-scattering reflectance distribution function*, which will allow images to be vivid and realistic.

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Yoichi Ochiai *is a PhD student at the University of Tokyo's Graduate School of Interdisciplinary Information Studies. His research areas include digital reproduction, computer graphics, display, media art, and human–computer interaction. Ochiai received a master's in interdisciplinary information studies from the University of Tokyo. He's a member of ACM. He has received the Super Creator Award from the Information-Technology Promotion Agency and the Ministry of Economy, Trade and Industry of Japan; the Best Paper Award from Advances in Computer Entertainment; and the Japan Manifest Award. Contact him at yoichi.ochiai@me.com.*

Alexis Oyama *is a researcher at the JiseCHI Future Imaging Lab. His research areas include computer vision, computer graphics, artificial intelligence, motion capture, and games. Oyama received a master's in entertainment technology from Carnegie Mellon University. He's a member of ACM. Contact him at alexis.oyama@gmail.com.*

Takayuki Hoshi *is an assistant professor at the Nagoya Institute of Technology's Center for Fostering Young and Innovative Researchers. He's interested in tactile sensors and*

displays. Hoshi received a PhD in information science and technology from the University of Tokyo. He won the 2007 Society for Instrument and Control Engineers (SICE) International Award. He's a member of SICE, the Robotics Society of Japan, the Virtual Reality Society of Japan, and the Japan Society of Mechanical Engineers. Contact him at star@nitech.ac.jp.

Jun Rekimoto *is a professor in the University of Tokyo's Interfaculty Initiative in Information Studies. He's also the deputy director of Sony Computer Science Laboratories. His research interests are human–computer interaction, computer-augmented environments, augmented reality, mobile and wearable computing, interaction techniques, information visualization, and VR. Rekimoto received a PhD in information science from the Tokyo Institute of Technology. He received the Multimedia Grand Prix Technology Award from the Multimedia Content Association of Japan in 1998, the iF Interaction Design Award in 2000, the Japan Inter-Design Award in 2003, and the iF Communication Design Award in 2005. In 2007, he was elected to the ACM CHI Academy. Contact him rekimoto@acm.org.*