Theory and Application of the Colloidal Display: Programmable Bubble Screen for Computer Entertainment

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Abstract. It is difficult to dynamically change the optical properties of ordinary screens. In conventional projection systems, the choice of screens is limited; and the brightness of projected images and the viewing angle are unalterable once a screen is fixed, even though demand for altering the viewing angle according to the locations and the requirements of installations exists.

The results of a study conducted by us indicate that a colloidal membrane can be used as a screen by vibrating it at a high frequency using ultrasonic waves. On the basis of those results, in this paper we discuss the implementation of a screen that allows us to dynamically change its brightness and view angle. We also discuss our investigation of its optical characteristics.

Our investigations reveal that the screen can be deformed by stronger ultrasonic waves, frames of various shapes can be used to create it, and that we can interact with it by inserting our fingers because it is made of colloidal solution.

Keywords: Colloidal Display, Entertainment Computing, Virtual Reality, HCI.

1 Introduction

All over the world, screens are used to display various digital contents, such as movies, presentations, and shows, and are essential in the field of entertainment. The fundamental process utilized to display content on a screen is as follows: digital content is created, the content is rendered, and the content is shown on a screen via a

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projector. A significant amount of information is lost when the content is shown on a static surface because ordinary screens are rigid and static and the texture of the screen cannot change dynamically. However, in the digital world, we can dynamically specify an object's texture by modifying its light and bump maps. Consequently, in our research, we are attempting to take the first step in bringing digital to physical by applying this computer graphics concept to screens in the real world.

We propose to control the optical characteristics of screens in order to reproduce the realistic appearance of contents, and thereby provide a new entertainment systems option. To realize this concept, we choose a colloidal film and excite it with an ultrasonic wave (Figure 1). The ultrasonic wave induces a minute wave (known as a "capillary wave") on the colloidal film that leads to an expansion of the viewing angle. To the best of our knowledge, ours is the first approach to utilize this phenomenon to control the optical characteristics of a screen. We can control the vibration of the screen at high frequency. In addition to expanding the viewing angle, we can induce an optical illusion to reproduce glitter by means of time division control.

The main application of colloidal screen [1] is control of reflection and texture. In addition, colloidal film is a unique material, which imbues a screen made from it with flexible characteristics such as screen deformation, physical popping, and actual screen reconstitution. The possibility exists for these features to be applied in entertainment computing.

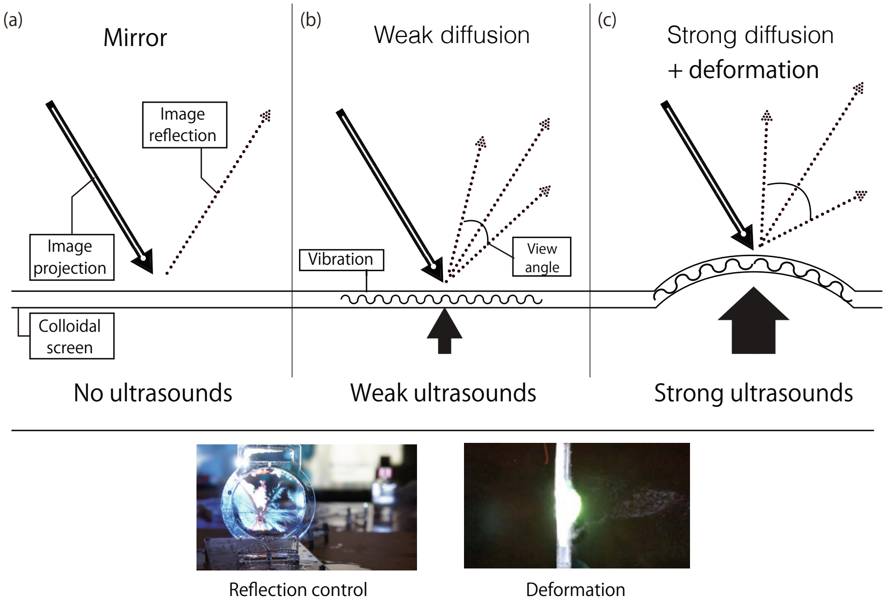

Fig. 1. The image is projected (black arrow with line) from the top. The ultrasonic waves (black arrow) hit the membrane to reflect the image (light dotted arrow). Note that there are two types of effects related to the intensity of ultrasound: A weak ultrasound mainly changes the viewing angle while a stronger ultrasound additionally changes the shape of the screen.

The remainder of this paper is organized as follows. In Section 2, we cite related research and discuss the reason why our research is relevant. In Section 3, we explain the theory underpinning our work. In Section 4, we give an overview of our system, including system requirements. In Section 5, we discuss an evaluation conducted by means of a laser experiment, and discuss prototype applications developed in Section 6. Finally, we discuss the limitations of our proposed system, Section 7, and conclude by looking at possible future work, Section 8.

2 Related Work

In our study, we dynamically change the shape and texture of the screen (Figure 1). Therefore, in this section, we cite researches that are relevant to active screens, and which either change the spatial position or the texture of an object. We then look at how our research relates to these relevant research efforts.

2.1 Texture Displays

In this subsection, we look at research done to control the surface textures of an active screen.

In [2], Raffle et al. proposed Super Cilia Skin, a conceptual interactive surface comprising thousands of cilia-sized actuators, and actually developed 128 magnetic cilia. Coelho and Maes [3] subsequently presented Sprout I/O, which expanded on the concept using Teflon actuators as cilia-like structures, which can actually bend and stretch, for the surface.

Furukawa et al. [4] presented FurDisplay, a surface constructed of fur and controlled with a vibrating motor. When the surface of FurDisplay is activated, the hair stands upright. By detecting capacitance change, it promotes interaction of people and fur. These researches are related to our research because they express the physical texture using actuation. They are good for wearable computing and interactive architecture, but the range of expression of textures are restricted and they are limited in terms of size and the limited ability provided by actuators for control.

Research is also being conducted on dynamic texture display. Hullin et al. [5] developed Dynamic BRDF Display, which changes the reflection parameter of the surface of water by vibrating it using actuators. This can diffuse reflection and blur images. This research can express BRDF that cannot be expressed in an LCD display such as that presented by Koike et al. [6]. Although it is a pioneering research, it is limited in terms of size and the fact that the orientation of the display cannot be changed.

2.2 Deformable Screens

Research geared towards controlling the spatial position of an active screen is also being actively pursued. Many of the systems researched were first used for tactile presentation [7]. For example, the system that Cholewiak et al. [8] developed in 1981 was used as a tactile skin display and utilized several actuators. The system displayed the vibratory stimulation using several cylindrical actuators that moved up and down. There are also other systems with similar mechanisms to that used by Cholewiak et al. [8]; for example, the deformable actuated screen “Project FEELEX” [9], which constructs 3D forms on the surface of the screen using an actuator array set under the screen. In addition, LUMEN, proposed by Poupyrev et al. [10], comprised actuated dot matrix LEDs—physical pixels shown in RGB and H (height). Leithinger et al. [11] also proposed an interactive deformable screen called Recompose.

Other researches dealing with control of the spatial positions of displays also exist. There are image projection technologies that use fog as a screen, such as the systems proposed by Rakkolainen et al. [12] and Lee et al. [13]. These technologies display images in the air using a fog screen and a camera. This is projected in the air as a result of fog's diffusibility characteristics.

Research on displays using water is also being conducted. Sugihara et al. [14] used fountain as a deformable water screen. Barnum et al. [15] developed a screen that uses the water drops in the air. Water drops have lens-like characteristics. By using these characteristics, they were able to project an image onto the water drops. They made a water drop sequence in the air and projected the image corresponding to the spatial position by synchronizing the projector with the water bulbs, and applied their technology to create a multilayer screen. Other interesting artworks include those presented by Suzuki et al. [16], which uses underwater air bubbles, and Kodama et al. [17], which uses magnetic liquid.

Displays have also been made using soap bubbles. Bubble Cosmos [18] is a technology that constructs a screen in the air by confining fog in a bubble; and Shaboned Display [19] turns a bubble into a pixel. Bubbles have also been used as a musical instrument [20].

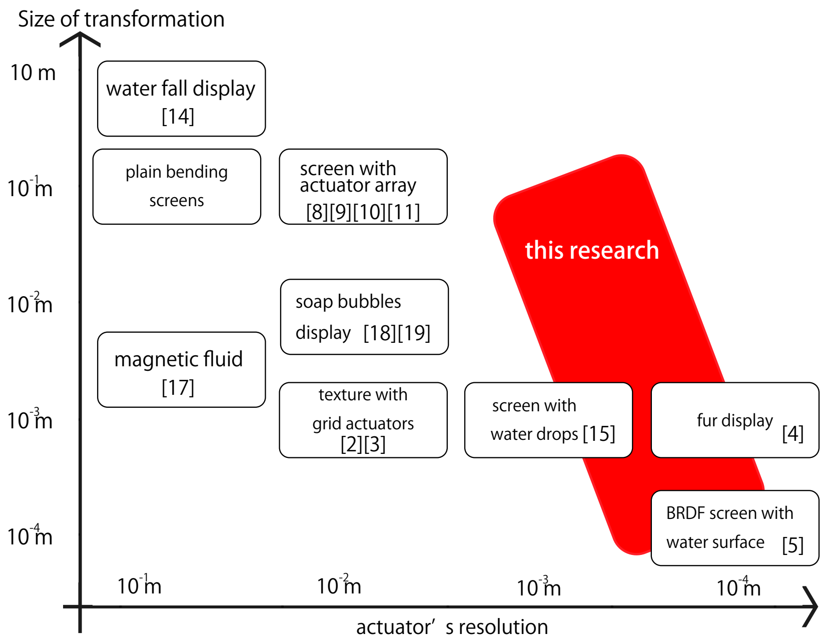

Fig. 2. Position of our research corresponding to other relevant researches. Vertical axis represents the amount of transformation dealt to the object while the horizontal axis represents the actuator's resolution. Notice how our research (red) covers the areas that have not been explored yet.

2.3 Position of This Study

Our research is positioned as shown in Figure 2. The size of the changes on the vertical and horizontal axes represents the resolution of actuation. For example, since a dynamic BRDF [5] changes the surface texture by detailed vibration, the resolution of actuation is high and the size of change is small. Researches on dynamic textures with small actuators are not high-resolution and the size of spatial change is limited.

Using this rationale, we positioned our research in the area colored in red. The actuator resolution of our research is high when the spatial change is small and low when the spatial change is large. No research equivalent to this domain exists. Our research contribution is high because we use the same hardware settings to accomplish many of the features achieved in related research.

3 Theory

In this section, we describe the theory underpinning the colloidal screen technology. First, we describe the capillary waves that are induced on the soap film, then introduce the reflection model of the colloidal display, and finally, describe the ultrasounds.

3.1 Capillary Waves on Soap Film

The 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 interface is described by Equation (1) [21].

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

where σ is the surface tension, ρ is the density of the colloidal solution and f is the excitation frequency. Wavelength λ is estimated from Equation (1). The surface tension of colloidal liquid σ is 0.07275 N/m (20 deg C). Suppose the surface tension of colloidal liquid to be 1/2 of water and density to be the same as water 1000kg/m^3. In this situation, with 40kHz ultrasounds, the wavelength λ is $2\pi/k=83\mu\text{m}$.

These minute waves (Figure 3) occur on the ultrasound-activated colloidal film and diffuse the light on the surface.

3.2 Reflection of Screen

Let us now look at the reflection model of the colloidal screen. The film surface reflection model used in the colloidal display is the bidirectional reflectance distribution function (BRDF). The BRDF expression is shown in Figure 4.

$$f_r(\omega_i,\omega_o)=\frac{dL_r(\omega_o)}{dE_i(\omega_i)}=\frac{dL_r(\omega_o)}{L_i(\omega_i)\cos\theta_i d\omega_i} \tag{2}$$

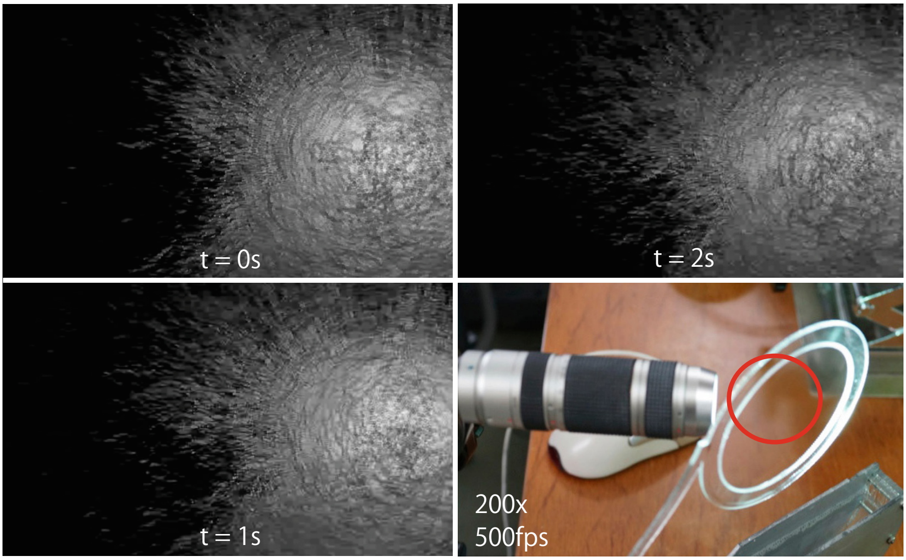

Fig. 3. Capillary waves on the colloidal film. (200x, 500 fps high speed camera capture image).

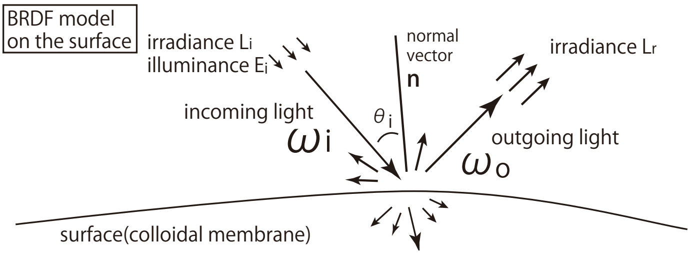

Fig. 4. BRDF model on the screen

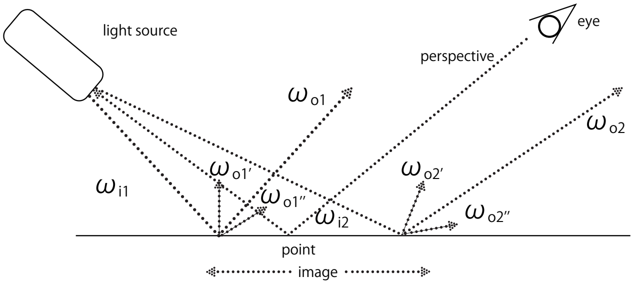

Fig. 5. View angle of the image

This expression is intended to represent the relationship between the direction of the reflected light (ω_o) and the direction of the incident light (ω_i) on the surface by E (radiance) and L (irradiance). Bidirectional transmittance distribution function (BTDF) also exists, but it is possible to ignore BTDF by specifying the state of the surface to only speculate BRDF, resulting in only front projection.

A uniform thin film surface that does not have the characteristics of diffuse reflection is close to being a mirror. We cannot project the image onto a mirror. For these reasons, the light emitted from the light source shown in the figure reaches the eyes via a dotted line in perspective, resulting in only a dot or a light source being seen on the mirror surface. However, it is possible to project images onto it by expanding the scope or the view angle of the reflected light in the presence of ω_o in the BRDF model. The expansion of the existing range of reflection is shown as ω_{ol}'' and ω_{ol}' for ω_{ol} in Figure 5. The perspective light source covering a certain range makes the image appear on the film. We project the image on the colloidal screen in this manner.

$$dE(\omega_i) = L_i(\omega_i)\, d\sigma^{\perp}(\omega_i) \tag{3}$$

$$\int_{\mathcal{H}_o^2} f_r(\omega_i \rightarrow \omega_o)\, d\sigma^{\perp}(\omega_o) \leq 1 \qquad \text{for all } \omega_i \in \mathcal{H}_i^2 \tag{4}$$

In our research, we can control the reflectance distribution to some extent, but we cannot control the radiation and absorption of the material. The relationship between radiance L_r and radiance L_i follows two formulas. It does not depend on the distribution ratio of ω_o. This indicates that a very bright image can be presented when ω_o is a narrow distribution.

3.3 Ultrasonic Waves

The phased array focusing technique is used to achieve a high-intensity ultrasound wave. The focal point of the ultrasound is generated by setting adequate phase delays of multiple transducers. In addition, the focal point can be moved to an arbitrary position by controlling the phase delays [22].

The acoustic radiation pressure, a nonlinear phenomenon of ultrasound, acts when the ultrasound becomes high-intensity. When an ultrasound beam is reflected vertically at the soap film, it is subjected to a constant vertical force in the direction of the incident beam. Assuming a plane wave, the acoustic radiation pressure P [Pa] is described as

$$P = \alpha E = \alpha \frac{p^2}{\rho c^2} \tag{5}$$

where c [m/s] is the sound speed, p [Pa] is the RMS sound pressure of the ultrasound, and ρ [kg/m^3] is the density of the medium. α is a constant that depends on the reflection coefficient of the soap film. In a case where there is total reflection, its value is two.

The phased array focusing technique is used to deform the screen within a localized area and activate the screen with more intensity.

The focal point of the ultrasound is generated by setting adequate phase delays in the multiple transducers. In addition, the focal point can be moved to an arbitrary position by controlling the phase delays. A trade-off exists between the spatial resolution and the array size. Theoretically, the spatial distribution of ultrasound generated from a rectangular transducer array approximates the shape of a sinc function [23]. The width of the main lobe (w [m]) is parallel to the side of the rectangular and is written as

$$w = \frac{2\lambda R}{D} \tag{6}$$

where λ [m] is the wavelength, R [m] is the focal length, and D [m] is the side length of the rectangular array (Figure 8). Our system can control the spatial position of focus and it contributes to activate the films partially.

4 Design

In this section, we look at the design requirements for the colloidal display and give an overview of the system.

4.1 System Requirements

The concept underlying our system is changing the appearances of images by switching the screen's reflectance at high frequency. Therefore, the system has to satisfy the following requirements:

- The film must be light and soft enough for its optical properties to be changed using vibration.
- The ultrasonic systems must be operated at high frequency.
- Colloidal frames must continuously supply the colloidal solution to the colloidal membrane, resulting in an extension of the membrane's life with high stability against the powerful ultrasonic waves.

To satisfy these requirements, we use a strong ultrasonic actuator power speaker to vibrate the screen remotely and use colloid film that, although it is made from light material that is weak and fragile, has a high surface tension and is flexible.

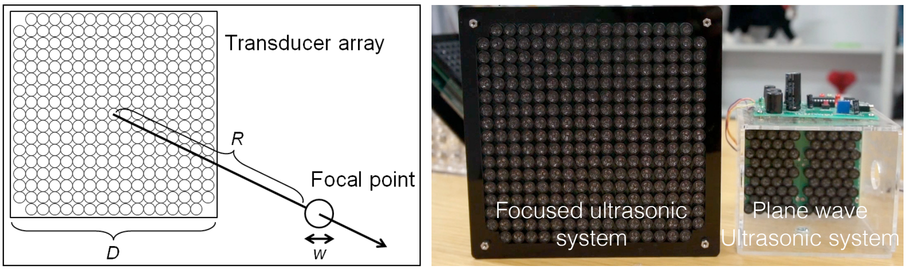

Fig. 6. Equipment for ultrasonic vibration

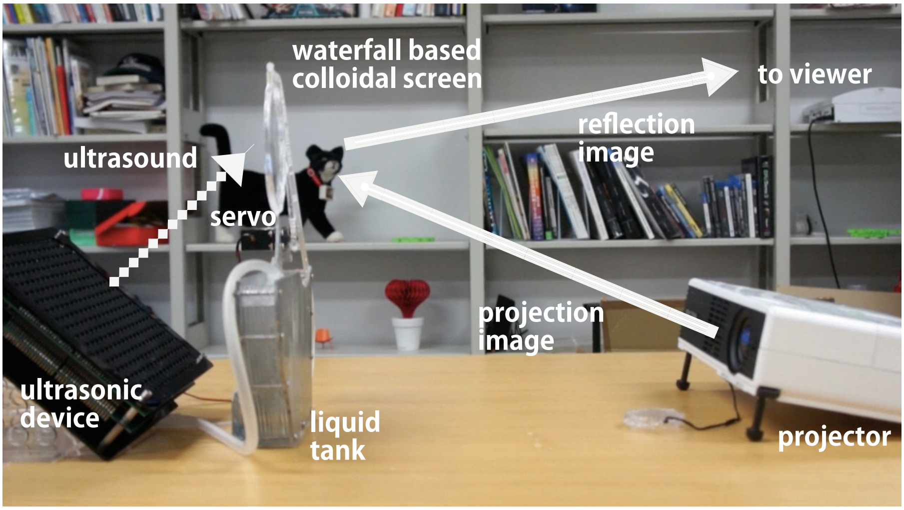

Fig. 7. Colloidal display system components: focused ultrasonic devise set on the opposite side of projector. The image on the screen can only be seen from the projector side.

Ultrasonic waves directly affect the reflection of the film, so if we switch the ultrasonic waves on/off, to human eyes, it appears as if a switch is being made from transparent to opaque.

4.2 System Overview

- LCD or DLP projector, such as a video equipment, which emits light.
- Colloidal film
- Film's frame with waterfall system and the mechanism to replace the film
- Equipments for ultrasonic vibration.

Table 1. Specifications of components

Projector	LCD or DLP	
Screen	Colloid solution	Soap
	Size of membrane	8 cm in diameter
Ultrasound	Transducers	285 pics
	Focus control	Phased array
	Frequency	40 kHz
	Size of focal point	2 cm at distance of 20 cm

Figure 7 shows one of the configuration that uses these components. Projector's light goes to the film and film's frame. Ultrasound waves are produced from the speaker simultaneously and hit the film, vibrating it. When the film is broken, it is replaced by servo-motors. The specifications of each part are described in table 1.

5 Evaluation

5.1 Laser Experiment

The colloidal screen's view angle varies when the intensity of the ultrasonic wave is changed or modulated. Figure 8 displays experimental results obtained using different ultrasonic waves. However, the same effect can be seen when the intensity and the focus length are changed. The more intense the wave is, the more view angle it creates. Looking at the BRDF equation, Equation (2) (Section 3.2), it is obvious that this means that it is changing parameter ω_o. We are able to control this parameter from zero to 90 degrees. Because the screen is vibrated intensely, the laser's reflection is not consistent. This is shown in Figure 8 (right), where t is time. There are slight differences in each image but the shape of the laser reflection is similar.

The graph of the brightness on each angle is shown in Figure 9. It shows that the narrow reflection angle (with low ultrasonic intensity) is bright in the center of the reflection and the brightness diminishes in the neighborhood of the center of the reflection. In contrast, the wide reflection angle (with high ultrasonic intensity) results in a gentle decrease in brightness.

This result shows that we can control the view angle and distribution of the brightness by changing the intensity of the ultrasonic wave. It indicates that the colloidal screen solves the problem of screen selection and enlarges the application of the projector screen.

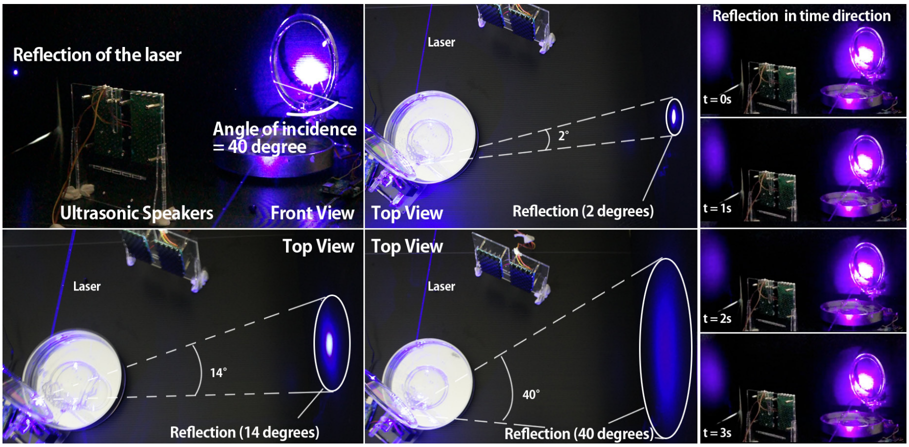

Fig. 8. Laser experiment example of wave form modulation. Different types of waves create different view angles. White noises create 40 degrees, sine waves create 14 degrees, and square waves create 2 degrees.

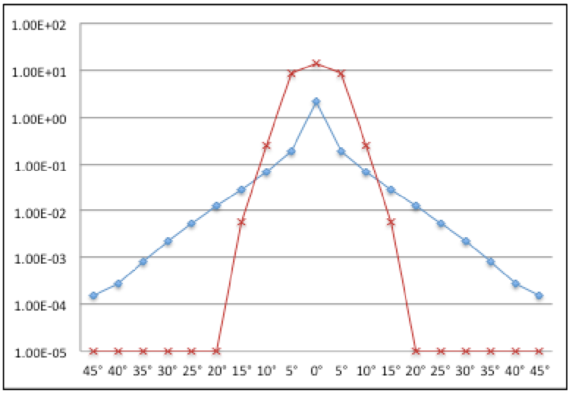

Fig. 9. This graph shows how view angle affects brightness. The red line has a small viewing angle but it is brighter than the blue line, while the blue line has a wider viewing angle but brightness is low.

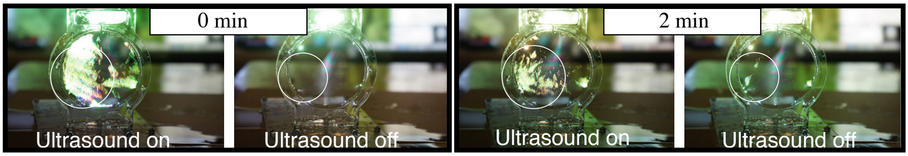

Fig. 10. From left to right the image quality decreases in relation to time due to water evaporation

5.2 Stability

In this subsection, we describe the retention time along with the stability of the colloid film. In our experiment, the colloidal film kept its membrane stable for three minutes on average when the ultrasonic waves were applied. The key component is water; the less water there is in the membrane, the more noisy the image. Figure 10 shows how the image quality changes with time. Observing the circle on the four images, it can be seen that the images on the left devolve into the images on the right over time. This is because as time passes the water evaporates, causing the transmission characteristics to be reduced, which results in the image being disturbed. The main reason for this disturbance of the display is failure to control the reflection characteristic.

6 Applications

We developed several prototypes that utilize the characteristics of the colloidal screen. In this section, we describe four sample applications of the colloidal screen that use different optical properties. The perspective screen uses the view angle, the plane-based 3D screen uses the transparency, the deformable screen uses the phase array to change the shape, and the bump mapped screen uses deformation with specifications.

6.1 Perspective Screen

We developed a display to show multiple images from multiple angles using the characteristics of the colloidal screen. The principle of operation depends on the characteristics of reflectance distribution of ωo for multiple light sources, as shown in Figure 11. Different projection sources provide several different images for each angle. The images are being multiplexed at the same time but one image can only be seen in one direction.

In this application, five components are needed: different directional light source, colloidal solution, frame for the membrane, film replacement mechanism, and ultrasonic oscillation. The installation position is shown in Figure 11.

We projected the image from above and decomposed a single image into three images by angling the three mirrors in different directions. We also set an ultrasonic oscillator behind the screen to operate it. The result is shown in Figure 11. There are three images: one from the left, one from the center, and one from the right. We set the left edge at r = 0 degrees and the mirrors at positions r = 45, 90, and 135 degrees. We adjusted the colloidal screen so that the reflection angle was 40 degrees (by ultrasonic modulation). The actual transition of the images is shown on the right side of Figure 11. The transition is smooth and there are no image overlaps.

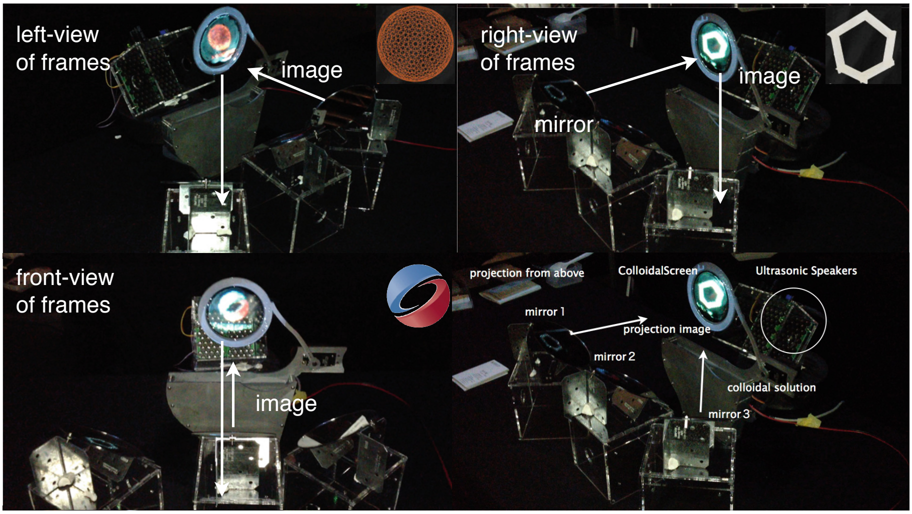

Fig. 11. (Perspective Screen) Three different images from different perspectives are shown. The top image viewed from the left, the middle from the center, and the bottom from the right.

6.2 Plane-Based 3D Screen

In this subsection, we describe the development of a 3D display using multiple planes (Figure 12). LCD displays have a problem when it comes to viewing multiple layers; because of polarization, it is not possible to display multiple planes at the same time. In this respect, the colloidal display has several advantages. This colloidal screen can display more than one plane at the same time, and the image is very bright.

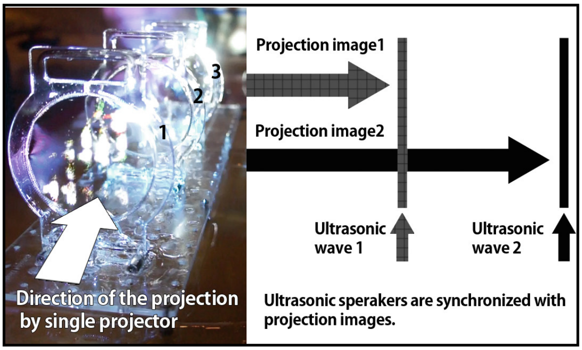

Fig. 12. (Plane based 3D screen) The transparency alternates within the 3 screens

We set up multiple sets of colloidal screen and ultrasonic speakers with ultrasonic oscillations synchronized with the projector. The installation position is shown in Figure 12. Each colloidal screen had an ultrasonic speaker that set its transparency. Toggling the transparency of each screen was achieved by simply turning the speakers on and off. The system was able to show three different images on each colloidal screen by controlling the transparency of each screen synchronized with the projector's images. This is effectively a 20 Hz time division plane-based 3D screen with a single projector.

6.3 Material Display

We also implemented a display that reproduces the appearances of various materials along the concept (Figure 13) in which different reflective states overlap in the time division. In the mirror reflection state, the light can be seen at a different area on the screen according to the viewpoint. No additional calculation is needed to render the images for projection because the reflection control is done on the screen. Moreover, reflection parameters are determined by two factors: the degree of mix in the time division and the power of the ultrasonic waves. This display has a simple structure but wide application range.

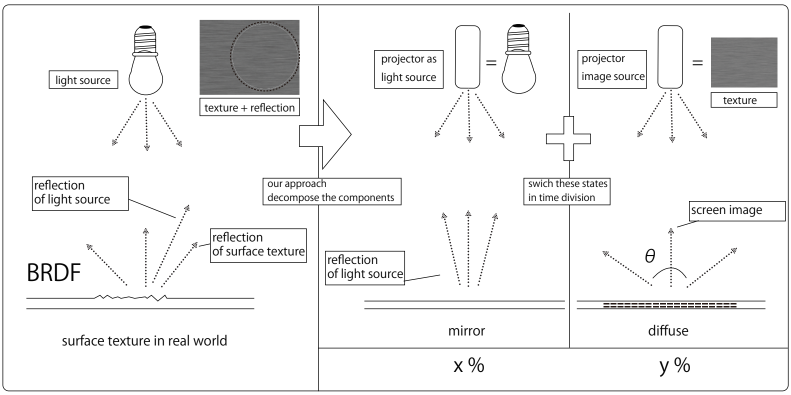

Fig. 13. Shows how we can mimic a texture in real world controlling the percentage between mirror (x%) and diffuse (y %) in time division

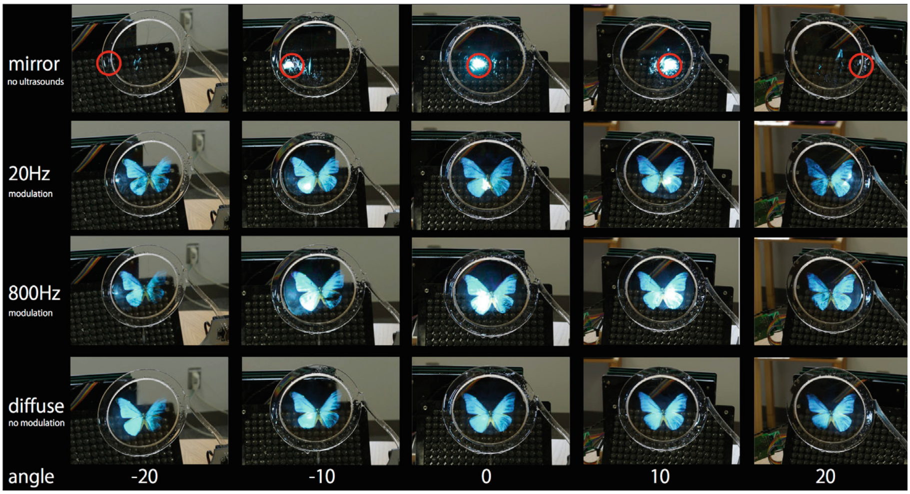

Fig. 14. Sample results for four reflective states from five different view angle. Note that red circle shows the reflective spot from the mirror and it is consistent with the bottom images.

Colloidal film is a unique material whose reflection range can be controlled. This characteristic, coupled with high frequency control of ultrasounds, facilitates this application. The results depicted in Figure 14 shows that our system successfully operated as a reflective display. It follows the reflection of the viewing point.

6.4 Deformable Screen

We also developed a deformable screen using the colloidal membrane. In this implementation, we used the ultrasonic speakers in two ways. One purpose was to change the reflection of the screen and the other was to create a deformation using the radiation pressure. The five components used are shown in Figure 7. The objective was to use the phased array to make a force field. The force field was generated by focusing the ultrasound in the range 25 cm and 15 cm. When the force field was created, it pushed the membrane, allowing it to deform.

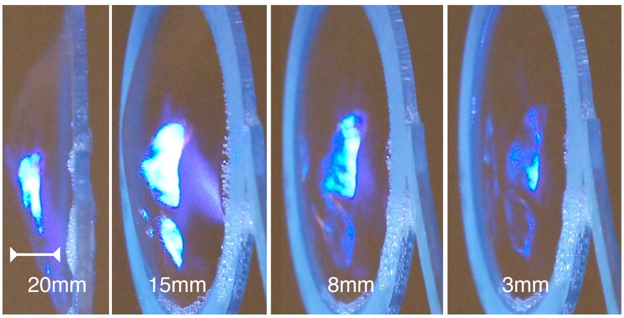

Fig. 15. Screen deformed from 2 mm to 20 mm

By controlling the focus and the spatial position of the force field, it was possible to change the size of the deformation point on the membrane from 2 mm to 20 mm (Figure 15). In addition, when two phased arrays were used we were able to control both the projection and the deformation.

7 Discussions

By turning soap film into a projector screen, we gained controllable properties such as flexibility, transparency, and durability. However, we acknowledge that a soap film does not last forever and there are limitations on the view angles. In this section, we first look at the limitations, then discuss the possibilities of our system for use in entertainment computing.

7.1 Soap Films Limitation

The amount of time a soap film can last depends on the humidity in the room, the power of the ultrasonic speaker, disturbance factors like wind, and the soap product. In our experiment, a soap film lasted an average of three minutes. We found an ingredient that can enable a soap bubble to last over a day by using a glue-like substance. However, this kind of material cannot create interactions such as popping. which regular soap film supports. In addition, soap film is flexible but has shape limitations. The shape has to be concave and cannot replicate complex shapes. This can be solved by using a polygon-like frame with multiple soap films.

7.2 Limitation on View Angles

The maximum view angle is 180 deg because this display is based on reflection. We achieved a maximum view angle of 40 deg. The view angle changes according to the intensity, the waveform of amplitude modulation, and the frequency of the ultrasound. If the view angle is too small, only the light is shown and not the content of the projected image because it is too acute for human eyes. However, we used this to our advantage and displayed three different images from different angles (we applied it to the perspective screen).

7.3 Outlook for the Entertainment Computing

A soap bubble is a unique material that users can insert their fingers into. Moreover, soap bubbles generate a lot of joy by their beauty and in our making and seeing them. Soap bubbles are used in the entertainment industry on occasions such as party events, and in theme parks and science museums. This technology can be applied in these industries to enable video projections on the bubbles. In this way, it can contribute to the expansion of the entertainment computing field.

8 Conclusion and Future Work

In this paper, we proposed an innovative first step to dynamically altering the brightness, shape, and view angle of screens by using soap film and ultrasonic speakers.

Many future potential projects are envisioned. One potential project is a dynamic 3D model with a minimal view angle and various images projected from different angles. This would be more cost effective than other methods such as holographic viewers. Furthermore, it would be interesting to see a 3D model made out of soap film on a polygon shaped frame (Figure 18) with several ultrasonic speakers. Many 3D models, such as those in games, tend to use the same models with different textures to create new enemies. The same concept can be applied to this display. Another usage for this display is to utilize its interesting interactive properties such as inserting and popping. For example, a game in which the player has to cut the screen to kill an enemy can be facilitated. In general, if we are able carry this concept to a bigger scale; it would open up many possibilities for the future of the entertainment computing industry.

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