Glass-beads Display: Evaluation for aerial graphics rendered by retro-reflective particles

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Abstract. We present a novel method for rendering aerial images using retro-reflective particles. Retro-reflective particles are composed of glass beads that are half-coated with mirror films. They reflect light in different directions without any significant reduction in brightness because the falling particles can rotate in all directions. We evaluate the proposed method through a comparison with conventional aerial screens, such as fog and gas.

Keywords: aerial imaging system · projector-screen · retro-reflective particles.

1 Introduction

There is a huge demand for aerial screens in the entertainment industry, because they extend the expression of imaging in the air. In addition, this allows images to be displayed in places where physical screens cannot be installed.

The fog display, which projects images onto fog screens formed by artificially generated mist, is the most common aerial screen [5]. In the last decade, the study of fog displays has shifted towards human-computer interaction research, and novel applications are constantly being proposed [4, 6, 7]. Fog screens are primarily used for entertainment and production; however, they contain several problems: (1) narrow field of view and image blurring due to Mie scattering, (2) Instability of the display screen due to turbulent flows, and (3) excessively bright projector light. Narrow viewing angles, of magnitude of 20 degrees or less, are also to be noted. In addition, direct light from the projector is often hazardous for children, and limits the design space between the projector and the screen.

We propose a novel aerial imaging system using the retro-reflective particle screen. Retro-reflective particles are composed of glass beads that are half-coated with mirrors [2, 8]. They are commonly used in road signs to provide highlights in the dark [3]. Here, the retro-reflective particles are arranged on the road signs to reflect the incident light.

We present an alternative application that uses glass beads as the aerial screen for augmented reality (AR). The proposed method possesses some advantages:

– Glass-beads display has a wide viewing angle because the incident light enters the retro-reflective particles rotated in all directions.

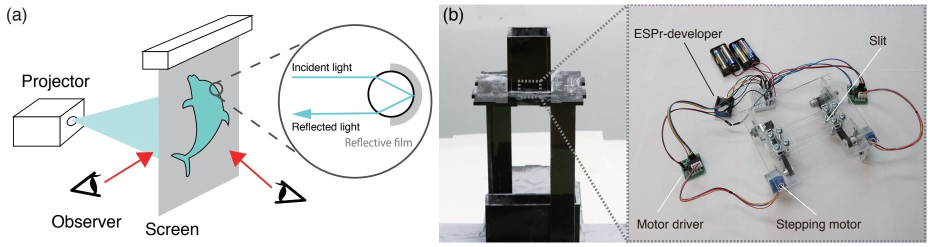

Fig. 1. The retroreflective particles fall from the control device. By projecting images from the projector on the screen, observers can clearly see the aerial images from all directions. (a) System overview. (b) Prototype and control device.

– By placing the projector towards the observer, one can see the aerial images without receiving direct light from the projector. Moreover, the screen has high luminance as the incident light is reflected by the mirror without scattering.

All aerial imaging systems have both positive and negative attributes; hence, we aim to contribute towards the study of aerial imaging systems by presenting a novel method for visualizing images in the air. In this paper, we quantitatively evaluate the characteristics of the proposed method. In addition, we conduct a comparative evaluation with existing aerial screens, such as fog and gushed displays. This paper is based on our previous study [1].

2 Glass-Beads Display

In this section, we describe the implementation of our system. Our system consists of retro-reflective particles, a control device, and a projector. In the proposed method, we form a screen comprising of the retro-reflective particles prepared by dropping these particles in air and projecting images using a projector.

2.1 Retro-Reflective Particles

The retro-reflective particles are made from glass beads that are mirror-coated on one side via aluminium evaporation, as shown in Fig. 1 (a). The coated inner surface functions as a mirror and the outer surface functions as a diffuser. In case the surface of the particle is not coated (i.e., clear), then the light entering on the bead will be refraction and transmission. On the other hand, when the entire surface of the bead is coated, the incident light diffuses because it is simply a spherical diffuser. However, because half-coated reflective particles have both transmission surfaces and retro-reflection inner surfaces, a see-through (transparent) screen with high luminance display is obtained.

Commercially, retro-reflective particle sales are rare; hence, they must be purchased directly from the vendor. We use UB-24MSJ (Unitika Ltd.) as the retro-reflective particle. The particle itself is 1 to 45 μm in diameter and $4.2\,\mathrm{g/cm^3}$. This particle size allows aerial images to be high resolution, and the particle weight is enough to fall vertically by gravity to form an aerial screen.

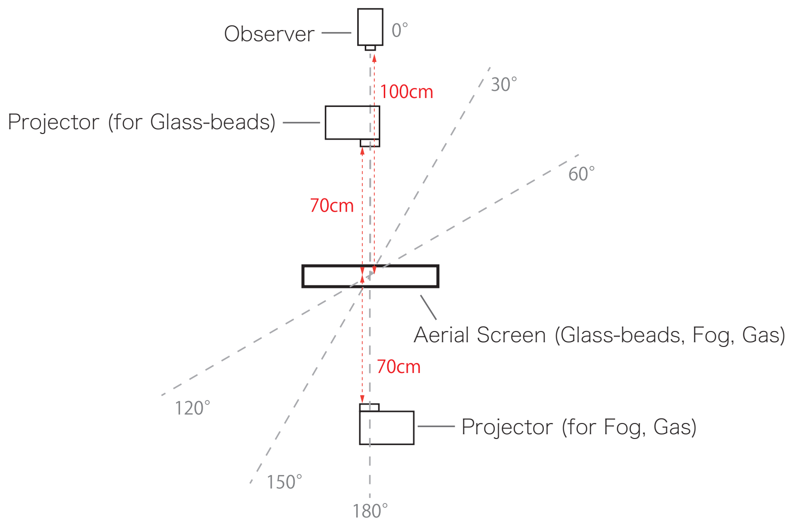

Fig. 2. Configuration of experimental setup. The observer represents people, cameras, and luminance meters. The same configuration was used in all the experiments. Note that the position of the projector varies but the distance from the screen remains the same.

2.2 Control Device

We constructed an aerial screen by dropping retro-reflective particles using a control device as shown in Fig. 1 (b). Retro-reflective particles pass through the slit and subsequently fall due to gravity. We can control the width of the slit using this system. The control device consists of an ESPr-Developer, a motor driver, and a stepping motor. In this paper, we set the width of the screen to 50 mm. The size of the device was 170 mm × 150 mm × 80 mm, and the weight of the device was 537 g. The control device opens and closes a slit between 1 mm. The slit of the screen nozzle was 50 mm × 1 mm. Wireless operation of the control device was enabled with the ESPr-Developer.

3 Experimental Evaluation

3.1 Experimental Setup

Figure 2 shows the setup for the experimental evaluation. We installed the projector and the aerial screen at a distance of 70 cm. The short focus projector TH682ST (BENQ)[3] is used for all sections of the experiment and user study. The display method was DLP, the resolution was Full HD (1920 × 1080), and the brightness was 3000 lm. The observer (e.g., human, camera, and luminance meter) is present/placed at a specific angle 100 cm

[3] https://www.benq.com/en/projector/home-entertainment/th682st.html (last accessed February, 12th, 2019)

away from the screen. We used three types of display for the aerial screen: glass-bead, fog, and gushed. Note that the position of the observer, the position of the projector, and the respective properties all remain the same. However, for the glass-bead display, a projector is placed between the observer and the screen. For the fog and gas displays, a screen is installed between the observer and the projector.

Fog Display A fog display was constructed to conduct comparative experiments. The hardware consists of an ultrasonic transducer, blower fan, blower PVC pipe, and 3D printed nozzle. The atomization capacity of the ultrasonic oscillator was 500 ml / h and the slit of the nozzle was 50 mm × 8 mm.

Gushed Display We also prepared a gushed display for comparative experiments. To build the gushed display, we referred to the study by Suzuki *et al*. [6]. A cooling spray employed for cooling the human body in sports was adopted as a gas.

3.2 Display Result

We captured photographs from each aerial screen (fog, gas, and glass-bead) at angles from 0 to 50 degrees, as shown in Fig. 3. All ISO were 6400, the F value was 8, and the shutter speed was 1 / 60. For all aerial screens, clear images were obtained from the front. However, as the angle increased the Mie scattering caused blurring on both the fog and gas screens.

Then, we captured the glass-bead screen from angles of 0 to 180 degrees, as shown in Fig. 4. The proposed method obtained clear results irrespective of the viewing angle.

3.3 Luminance and Viewing Angle

We measured the luminance with respect to the viewing angle for each display. The procedure for measuring the luminance is as follows.

1. Construct an aerial screen of fog, gas, or glass beads.
2. Place the luminance meter at a distance of 70 cm at an angle of N degrees.
3. Project a white image from the projector.
4. Considering the turbulence of the screen, five measurement values are recorded and averaged.
5. Change the angle N with increments of 10° in a range from 0° to 80°.

We employed LS-160 (KONICA MINOLTA, INC.)[4] as a luminance meter. All experiments were conducted in a dark room.

[4] https://sensing.konicaminolta.us/products/ls-160-luminance-meter/ (last accessed February, 12th, 2019)

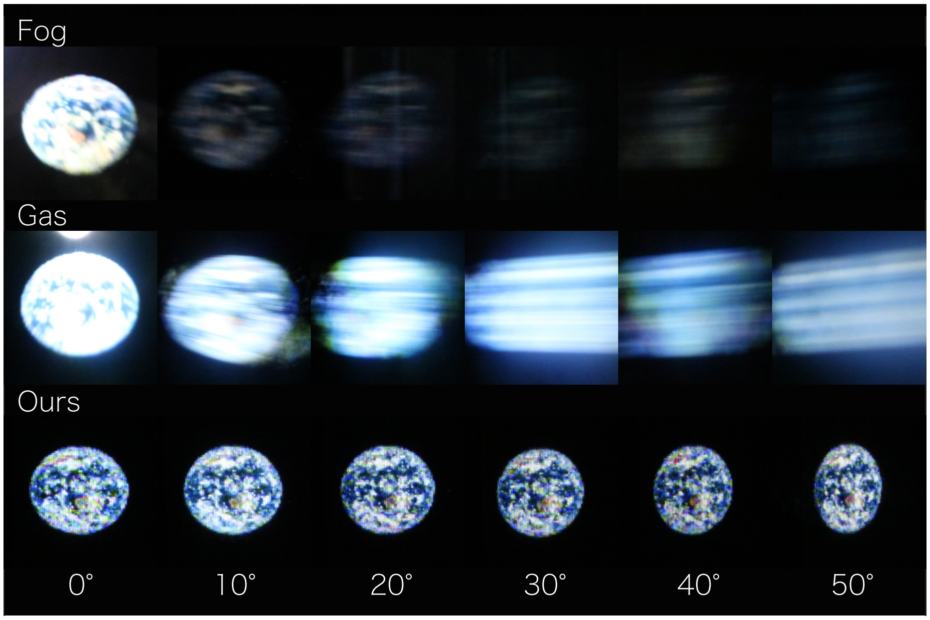

Fig. 3. Comparison of images obtained from different angles on fog, gas, and glass bead screens.

Result The luminance values in the case of center (i.e., 0°) was 89.93 cd/m^2 for fog, 506.82 cd/m^2 for gas, and 119.86 cd/m^2 for ours. From the results, the gas screen possesses the highest brightness value. Glass beads possessed higher brightness values compared to the fog screens.

Figure 5 shows the decrease in luminance versus angle. The horizontal axis represents the angle and the vertical axis represents the normalized luminance. The luminance in fog and gas screens sharply decrease at 20 degrees. The luminance becomes 10% or less when the fog is 20 degrees and the gas is 40 degrees. In addition, it was difficult to measure the luminance over 80 degrees. Contrarily, though the luminance of the glass bead screen decreased by 50% at 10 degrees, a detectable luminance value was obtained even at 80 degrees.

4 User Feedback

We conducted a user study with 15 participants (13 males and 2 females, with a mean age of 21 and a standard deviation (SD) of 3.43) for evaluating the performance of each aerial screen.

4.1 Procedure

Three screens of fog, gas, and glass beads were arranged side by side, each with the configurations as follows Sec. 3. To prevent the participants from identifying the material

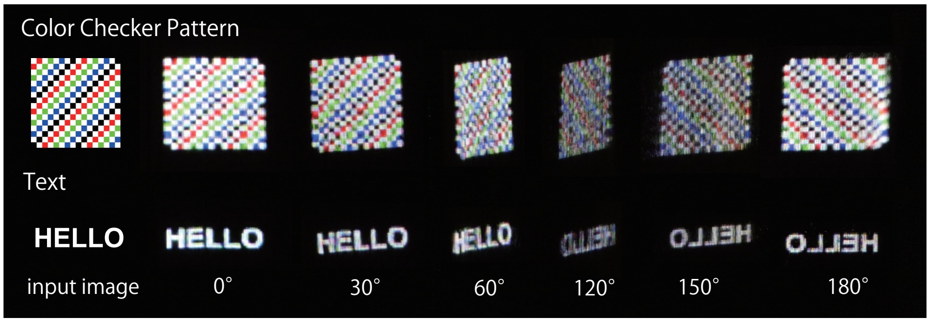

Fig. 4. Photograph of the projected image of colored checker pattern and text at each angle. Input image is shown in the leftmost column.

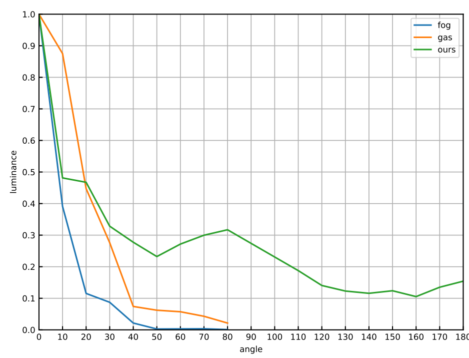

Fig. 5. Decrease of the luminance value with respect to the angle. The maximum value is 1 and the ratio is as shown. Glass beads possess a wide viewing angle, whereas fog and gas possess a large brightness value (depending on the viewing angle).

of the screen, each screen was called display 1 (fog), display 2 (gas), and display 3 (glass beads) during the experiment. We projected three images of earth, text, and a colored checker pattern on each screen. Participants observed the images from the front of each display. Each image (earth, text, and checker pattern) was displayed for approximately 5 seconds. Subsequently, the participants were asked to rate each screen on a scale of 1 to 5, where 1 = poor, 2 = unsure, 3 = fair, 4 = good, and 5 = excellent. The screen features being rated were as follows:

- Luminance: bright or dark.
- Contrast: high or low.
- Sharpness: sharp or blurred.
- Visibility: easy to see or hard.
- Prefer: like or hate.

After observing displays 1 to 3, the participants could re-observe another display and were able to update their ratings. After observing from the front, the experiment

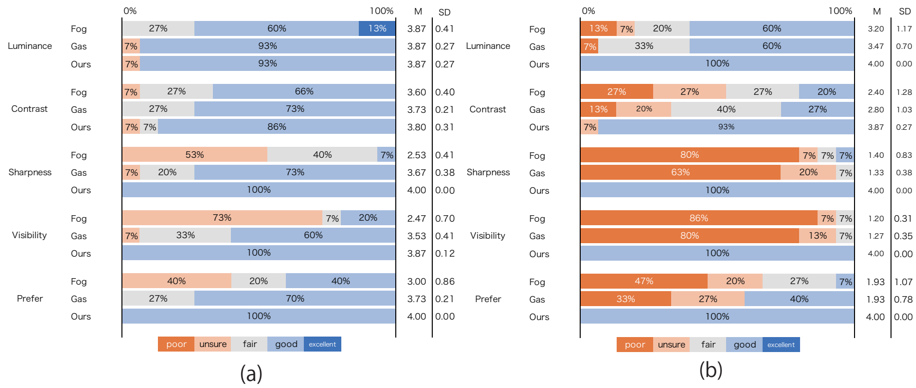

Fig. 6. Results from user feedbacks. (a) Observed from the center. (b) Observed from an angle of 30 degrees.

was conducted for observations from an oblique angle of 30 degrees using the same procedure.

4.2 Results

The results of the questionnaire are shown in Fig. 6. Our method recorded a higher average value than fog and gas screens despite the viewing angle (front or obliquely) for all the rated features.

When observed from the front, it was equivalent in luminance/contrast, but its sharpness/visibility was higher than both fog and gas. When observed from an angle, the contrast/sharpness/visibility of glass-beads screen was higher than both fog and gas. Moreover, its luminance did not change substantially, as compared to the other screens. Participants preferred our method in both the cases. Further, unlike fog and gas, our approach is robust against viewing angle.

5 Discussion and Future Work

5.1 Risk

We emphasize that the particles itself does not pollute the atmosphere and are safe to touch. However, because the size of the particles is exceedingly small, a risk similar to that associated with volcanic ash exists. Accordingly, it is necessary to prevent them from entering the body and inhalation through the mouth and nose must be avoided. Wearing a dust prevention mask could be a solution, but wearing such masks creates negative user experiences for the observers.

5.2 Sustainability

It is impossible to reuse the retro-reflective particles in event of the inability to collect them back. The projectable time of the aerial image depends on the number of beads. For instance, we dropped 1 kg of beads from the 50 mm $\times$ 1 mm slit and were able to project the image on the aerial screen for 60 seconds. Because the projection time per particle number is not very long, it is necessary to be able to reuse the glass beads for longer projection times. Retro-reflective particles in itself can be reused multiple times as they do not wear. For reusing these particles, methods such as sucking up the particles with the help of a vacuum cleaner or lifting them (such as on a belt conveyor) can be used.

6 Conclusion

In this study, we presented a novel method to visualize aerial images using retro-reflective particles and evaluated its display quality, luminance, and viewing angle. The results from the quantitative evaluation and the user feedback indicated that our proposed screen has a wider viewing angle, better sharpness, and higher contrast compared to the conventional screens such as fog and gas. Our system enables the exploration of new application areas for the aerial imaging system and the expression of AR.

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