3D Fog Display using Parallel Linear Motion Platforms

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***Abstract*—Fog screens have been widely used in theme parks and exhibition halls for entertainment and advertising purposes as the semi-transparent images suspending in the mid-air can create impressive *pseudo 3D* effect. However, conventional fog screens are flat and the projected images are not true 3D in nature. This paper suggests a new 3D fog display that exploits spatial projection mapping technique on a non-planar, reconfigurable fog screen to display volumetric data in real 3D space. The fog screen is composed of columns of upward-flowing laminar fog that are traveling on a set of linear motion platforms. The light beams from the projector are scattered at different depth positions on the fog screen, thus allowing the viewers to perceive three-dimensionality intuitively. The 3D fog display does not require any headgears or eye-tracking equipment while allowing full color 3D image to be observed by multiple simultaneous viewers. The immaterial nature of fog screens can also facilitate interesting tangible interactions in three physical dimensions. We have constructed a prototype display unit and developed a software platform to render the projection video and control the stepper motors of the linear motion platforms in order to synchronize the fog screen with the projection. The performance of the proposed display is verified by a number of real display examples.**

Keywords—volumetric displays; spatial projection mapping; mixed reality; fog screens

I. Introduction

3D displays have a wide range of applications in all disciplines, from art, design and entertainment, to engineering and scientific visualization, medical imaging and tele-presence. Many related technologies have been developed over the past decades and several works have made remarkable achievements. The autostereoscopic display developed in [1] used a rapid-spinning mirror to reflect the light field images from a high-speed projector and render a 360º observable image. Similar mechanism has been employed by [2], [3] and many other swept-volume displays to produce a series of fast-moving slices of the 3D object and base on human's persistence of vision POV to fuse the slices into a single 3D image. The image space of these systems are usually small and enclosed in a container that is not reachable by users. [4, 5] used laser-plasma scanning to create an array of illumination points in mid-air. The display can only produce sparse (low resolution) and single-color luminous points. Also, the use of high power laser beam would induce safety concerns. Recently, Pixel Dust presented in [6, 7] used acoustic-potential field to trap and levitate small, light-weight objects by standing waves and create patterns for projection. This approach cannot be used for high-resolution volumetric display as only a low-density, 2D layer of particle pattern can be created at a time.

There are a number of interesting research works that used fog or other immaterial medium, such as water, smoke and particles, as projection screens to create unencumbered 3D visuals. [8] presented a walk-through fog display that could create depth cue by head tracking and rendering corrected perspectives. This system can only accommodate a single user and wearing infrared LED headset is required for the camera to detect the viewer's location. A technique called depth-fused 3D (DFD) [9] creates 3D perception by superimposing two images on two transparent screens at different depths while varying the luminance [9]. Therefore, DFD is suitable to be used with mid-air, immaterial displays such as fog screens. In [10], the same researchers from [8] used the generalized form of DFD and put two fog screens in multiple configurations to create 3D perception. However, this approach is, again, viewpoint-dependent and demands precise tracking of viewer's position. Also, it can only accommodate one viewer at a time. Besides, motion parallax is another technical for creating 3D perception. [11] presented a multi-viewpoint fog display that uses multiple projectors to project multiple images of the same virtual object from different viewpoints onto one cylindrical fog screen. When walking around the display, observers can perceive the 3D shape of the object based on motion parallax. The angle of projection between each projector for this approach should be kept small enough to avoid "gaps", thus many projectors are needed to facilitate a wide observable angle. [12] proposed a multi-layered water drop display that uses a projector-camera system to synchronize the valves and image. This system requires high-speed camera and compute-intensive control with GPUs to achieve precise drop synchronization. Besides, the drawback of using water drop is that, it is difficult to achieve high-resolution display as each water drop represents only one pixel. Moreover, handling water is less convenient and infrastructures including drains and waterproof measures are required. The droplet size of fog or mist makes it easily disperse and evaporate into the air, thus fog screen can be used in all venues with effortless handling.

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Here, we present a novel volumetric display that is elaborated on the conventional fog projection technique. Our fog screen is created by a set of fog emitter modules that are mounted on and moved by linear motion platforms. The flat fog screen is then converted to a non-planar, dynamically reconfigurable surface for scattering the projected light. In this paper, we will first describe the display mechanism of the proposed approach and the design details of our prototype. We also provide a simple calibration method to obtain the required parameters for mapping the projection correctly to the fog screen. Finally, we evaluate this piece of work by displaying static objects and animations with the prototype display unit. This paper concludes by giving the briefs of a few directions for further developments of this project.

II. Methodologies

A. Preliminaries

This subsection describes the mechanism of the proposed volumetric display and provides the notations and assumptions used in this paper. As shown in Fig. 1, the system consists of a calibrated projector and an array of fog emitter modules that produces columns of upward-flowing laminar fog. Each fog emitter module is mounted on a linear motion platform and traveling along the direction of the projector's principle axis. The laminar fog forms columns of immaterial screens that scatter the light being projected onto it. A clear and bright image can be observed from forward and reverse directions along the projection axis owing to Mie scattering. The motion of the linear motion platforms is tightly synchronized with the image content.

Suppose the fog display consists of m fog emitter modules distributed in x direction and travelling in z direction. The projection image can be vertically divided into m segments. Each segment i is associated with a designated depth for projection. Moving the fog emitter modules to different depths will create a non-planar fog screen that can be used for displaying volumetric data in real physical space. We have developed a software to automatically transform the image segments in order to correct the distortion arising from the projective geometry on the non-planar screen. When the system is used to display dynamic content such as 3D video, animation and interactive game, the software will send synchronized control pattern to the microcontroller so that the fog screen elements are reconfigured accordingly.

We fix the origin of the world coordinate system at the centroid of the image space. The projector is precisely aligned such that its coordinate system is in a pure z-translation from the origin of the world coordinate system (projector's principal axis overlaps the world z-axis). The distance between the projector and the fog screen is denoted by d. The width, length and height of the image space are denoted by W, L and H respectively, where H is obtained by measuring the minimum height of fog that can produce clear image. The linear motion platforms are precisely aligned and evenly distributed. The distance between the nozzles of two fog emitter modules in x direction is denoted by δ_x. Let $X=(x, y, z)^T \in \mathbb{R}^3$ be a point in the world coordinate system, and $\boldsymbol{u}=(u, v)^T \in \mathbb{R}^2$ denotes the pixel coordinates of the image of point X in the projection plane.

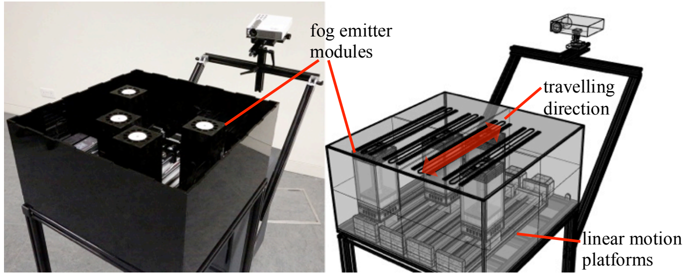

Fig. 1. Overview of 3D fog display unit.

B. Calibration

In order to map the projected image correctly to the non-planar fog screen, the projector's pose and parameters must be carefully calibrated. We propose a simple and effective method to align and calibrate the projector. The procedures are described below:

Step 1. Align principal axis with world z-axis

We have used a calibrated camera and the code given by [13] to calibrate the projector's intrinsic parameters as well as the radial and tangential distortion. However, we found that the skew coefficient and lens distortion were insignificant and could be ignored in our case.

Then, two checkerboards were attached to the front and rear planes of the image space. We projected a cross pattern on both checkerboards. The projector's position and orientation are adjusted using fine adjustment apparatus such that the cross pattern and its center align precisely with both checkerboards. This procedure can effectively align the projector's principal axis with the world z-axis. It strictly constrains the projector's orientation and x-, y- locations while leaving only 1-DOF for it to translate along the z-direction. The projector's focal point is set to the origin of the world coordinate (centroid of image space).

Step 2. Compute projection distance and field of view

We then measured the actual projection distance d and the horizontal pixel dimension M_0 on the front plane. These parameters will allow us to evaluate the display resolution (total number of voxels) and map any point from world coordinate to pixel coordinate. M_0 can be easily measured by reading the pixel coordinates on the left and right edges. To accurately measure d without the use of expensive distance sensing equipment. We project a checkerboard pattern on the front plane and scale the pattern while fixing the center so that the projected checkerboard overlaps perfectly on the printed checkerboard. The pixel coordinate u_1 is saved. We then apply the same procedure on the rear plane and save the pixel coordinate u_2, where u_1 and u_2 are related by $u_1 = su_2$ and s is the scaling factor. The projector distance can be computed by:

$$d = \frac{L}{s-1} \tag{1}$$

Notice that, in (1), d is independent of W and H. Let θ_x and θ_y be the horizontal and vertical field of view (fov) of the projector, we have:

$$\theta_x = 2\tan^{-1}\left(\frac{MW}{2M_0 d}\right),\ \theta_y = 2\tan^{-1}\left(\frac{NW}{2M_0 d}\right) \tag{2}$$

where M and N are the native pixel dimensions of the projector. Note that, projectors usually have a claimed fov or throw-ratio provided by the manufacturers. (2) provides an evaluation and we can obtained an accurate measure with a large sample size. Furthermore, the scale s_j of each object j relative to the front plane can be expressed by

$$s_j = \frac{d}{d_j} s \tag{3}$$

d_j is the distance of object j from the projector's focal point. And the pixel coordinate u_{ij} of object j can be solved by simple trigonometry:

$$u_{ij} = \frac{(2i\text{-}m\text{-}1)\delta_x s_j M_0}{2W} \tag{4}$$

C. Design and Fabrication of Prototype

We have fabricated a prototype of the proposed 3D fog display using four high precision (0.02mm) linear motion platforms. The platforms are driven by stepper motors which are controlled using motor drivers and an Intel Galileo Gen 2 microcontroller. The pulse frequency and initial positions of the platforms are precisely calibrated so as to ensure accurate position and speed. The updated positions are stored in the EEPROM of the microcontroller.

The fidelity of any fog display system highly relies on the steadiness of fog flow because turbulent flow will cause severe image distortion from off-axis viewing angles. To ensure laminar flow while allowing the fog columns to be able to move along the projection direction, we constructed a set of stand-alone fog emitter modules and placed each of them on a linear motion platform as shown in Fig 1.

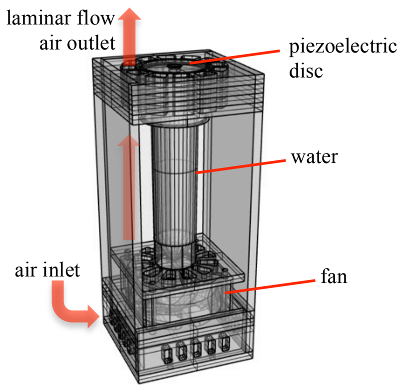

Fig. 2. Internal structure of fog emitter module.

Fig. 2 shows the internal structure of the fog emitter module. We used ultrasonic piezoelectric discs to generate high frequency oscillation in a film of water and produce microscale droplets that suspend in the air. Each piezo disc is attached to a sealed water container with a cylindrical sponge to act as capillaries and supply water continuously to the disc. There are ventilation holes at the base for air intake. An electric fan is placed below the water container to bring accelerated airflow continuously from the base to the top inside the module. There are arc-shaped vent holes around each nozzle on the roof of the module to ensure even airflow around each nozzle to limit the droplet spray angle. The diameter and height of the fog columns can be adjusted by controlling the piezo disc's oscillating frequency and fan speed. Fig. 3 shows the laminar fog columns formed by the fog emitter modules of our prototype.

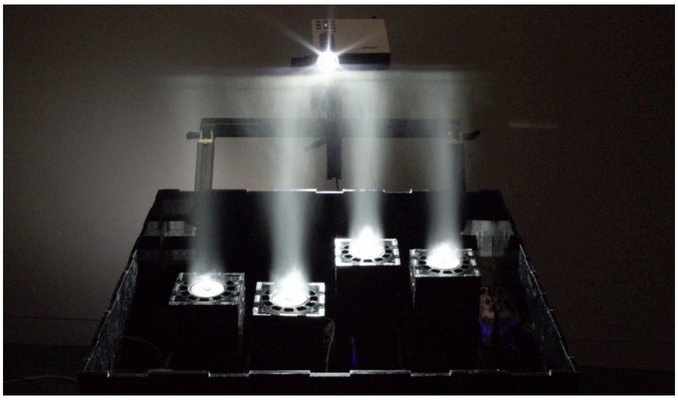

Fig. 3. Fog columns that exhibits laminar flow were formed by fog emitter modules.

III. EXPERIMENTS

We have implemented the methods presented above and developed a software in Processing. Our projector model is ASUS P2B that has an official throw ratio 1.1 (i.e. $\theta_x = 48.8^o$, $\theta_y = 31.7^o$) and native resolution 1280 by 800 pixels. The measured fov is $\theta_x = 46.9^o$, $\theta_y = 30.4^o$. The nozzle distance is $\delta_x = 95mm$. The dimensions of image space are $W{:}500mm$ by $L{:}500mm$ by $H{:}200mm$, H is the measured fog height. Three sets of experiments are presented below.

A. Example 1: Static Objects

In the first experiment, we used the Stanford bunny model to test our display with different fog screen configurations. First, we tested its performance using single and multiple fog emitters to display one image object. As shown in Fig. 4, four bunny models were projected on the fog screen. The bunny images appeared to be very clear with high quality of 3D details. When relocating the bunnies to different positions, the software automatically moves the fog emitter modules so that the fog screen is reshaped to show the bunnies at corrected positions. The depth and relative positions can be naturally perceived. Moreover, the tests have verified that our image transformation method can precisely scale and translate the objects to their desired sizes and positions in the image space.

B. Example 2: Static Background and Moving Objects

In the second experiment, static and moving objects were being displayed in the 3D fog display simultaneously. A Christmas tree image was displayed at the left hand side of the image space. An animated gif resembling a spinning planet was shown at the right hand side while its center was not moving. Another animated gif resembling a cartoon deer was traveling a linear path at constant speed.

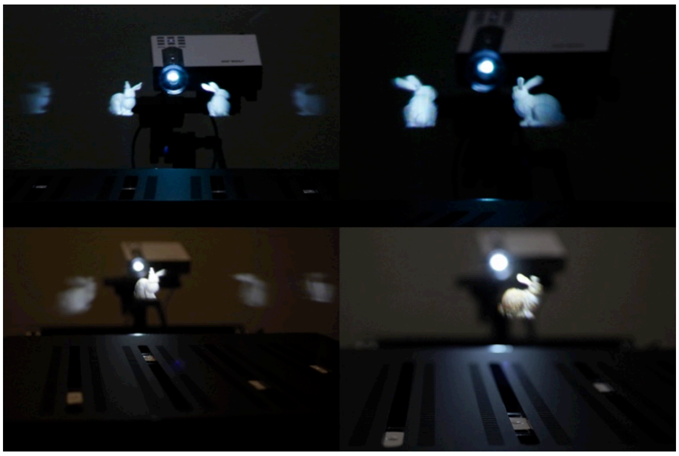

Fig. 4. Example 1: Stanford bunny models being displayed at different positions in the real physical space.

Fig. 5. Example 2: static and moving objects being displayed simultaneously.

C. Example 3:Moving Object Traveling in a Circular Path

The performance of the display was further verified using a famous bistable optical illusion called the Spinning Dancer. Rather than just spinning around at a fixed location, the figure was given 3D circular path as shown in Fig. 6. Unlike Example 2 where the deer were making a linear motion at constant speed, the dancer's velocity along z axis was not constant, thus the platforms needed to move at varying speeds. The result of this example has demonstrated the good 3D display quality and nice continuity of moving.

The video documentation of Example 2 and 3 is available at: *http://youtu.be/pMoqkYtdnPE*.

IV. FUTURE WORKS AND CONCLUDING REMARKS

This paper has presented a novel volumetric display that projects a 2D image onto a non-planar, reconfigurable fog screen. The proposed display creates image in mid-air in the real physical space thus creating immersive, true 3D experience. We plan to extend this work in a number of aspects. We will test using multiple projections from two or four directions to further enhance the range of viewangles. The most powerful feature of 3D immaterial display is the potential to create new interesting possibilities for tangible interaction and the interplay between virtual and physical objects. We will test using a number of motion or gesture sensing devices, such as infrared camera, Leap Motion and Kinect, with the fog display system to facilitate touch, reach-through interaction and augmented reality.

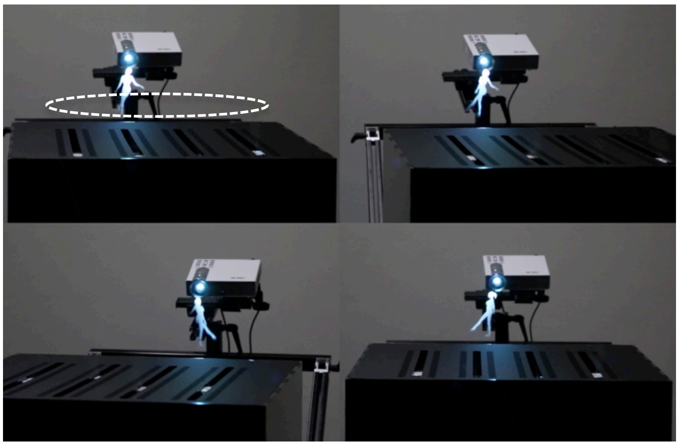

Fig. 6. Example 3: The Spinning Dancer figure travelled around a circular trajectory in 3D space.

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