Aerial Volumetric Display with Femtosecond-Laser-Driven Colored Voxels

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ABSTRACT

A volumetric display is capable of creating three-dimensional images in physical space by generating light emission, scattering or absorption points. We introduce two coloring methods of femtosecond-laser-driven aerial voxels for a volumetric display. One method extracts an arbitrary color from broadband emission of a voxel using two parabolic mirrors and a liquid-crystal color filter. The other uses scattering light of laser-excited aerial plasma. These methods produce color volumetric images in free space which have robustness to withstand collision with object.

1 Introduction

Volumetric display is a technology that spatially generates emission, scattering or absorption points as volume pixels (voxels) to create a 3D image that can be viewed from surrounding directions like a real object. By contrast, the natural properties of objects in physical space, such as volumetric 3D information, colors, robustness, and seamless relationships with people and objects, make this display difficult to implement on a practical level. Acoustic levitation displays [1, 2], photophoretic-trap display [3], and ultrashort pulse laser-excited plasma display [4] have been proposed as methods to display volumetric 3D images in free space without a screen. Technologies that use scattered particles, such as acoustic levitation and a photophoretic-trap, allow the color of the image to be changed freely by introducing illumination light. The ultrashort laser-pulsed plasma display can create robust images enough not to be destroyed by user or object contact, thus enabling interactive expression.

In this presentation, we introduce aerial volumetric displays using femtosecond-laser-driven colored voxels. These enable color representation of volumetric 3D images displayed in free space and also ensure robustness. One method is color extraction from a laser-excited voxel based on drawing space separation (DSS) [5]. DSS is implemented by aerial re-projection using two parabolic mirrors and a liquid crystal (LC) color filter to separate the space where the user view the image (viewing space) from the space where the image is drawn (drawing space). This separation extracts only the desired colors from the emitted colors covering the visible region and displays them in the drawing space. The second is color representation using scattered light from laser-excited plasma for an even wider field of view. We observed that the color of the aerial plasma produced by a 515 nm femtosecond laser changes depending on the polarization of the incident light.

2 Volumetric display system

Figure 1 shows a volumetric display system. Volumetric image is rendered by the persistence of vision occurring during the high-speed scanning of an aerial plasma as a voxel generated by femtosecond laser with 800 nm and 34 fs. The system generated a voxel to the drawing space after passing through a liquid-crystal on silicon spatial light modulator (LCOS-SLM) and a 3D beam scanning system. The laser pulses were modulated its phase to increase the number of voxels by a computer-generated hologram (CGH) displayed on an LCOS-SLM. The 3D beam scanning system constructed from a galvanometer scanner and a variable focal lens performed voxel arrangement to produce volumetric images by enabling spatial scanning of a focal point.

3 Results

3.1 Drawing color volumetric images based on DSS

Figure 2(a) shows a voxel re-projection system for DSS. The voxel in the drawing space was selectively extracted from an original emission with only arbitrary colors using the re-projection system constructed from two parabolic mirrors and an LC color filter. A Xe-filled cylindrical glass cell was employed as drawing space to generate a bright voxel.

Figure 2(b) shows volumetric image of bunny produced by pulse irradiation at 203 μJ using the vertex coordinates of a 3D model. The images were formed by stacking 2D cross sections of 3D point cloud data sliced into layers, and captured with an exposure time of 5 s.

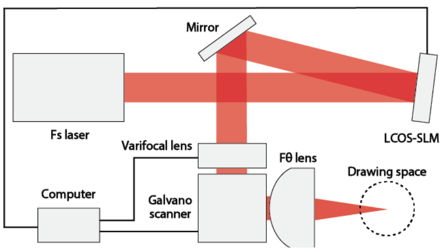

Fig. 1 Experimental setup

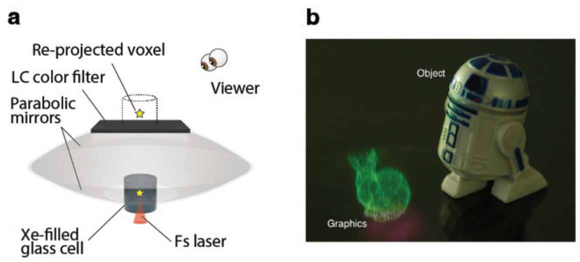

Fig. 2 (a) Voxel re-projection for DSS. (b) Volumetric image generated beside a physical object.

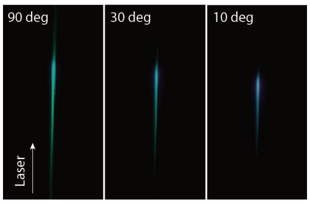

Fig. 3 Aerial plasma produced by a 515 nm femtosecond laser with different polarization.

The green color was expressed by applying pixel values of the LC color filter (R, G, B) to (0, 255, 0). The result demonstrated that the proposed system could create volumetric images in the air with desired color.

3.2 Colored voxels via scattering of plasma

Figure 3 shows an aerial plasma voxel produced by a 515 nm femtosecond laser. A voxel generated by polarization that was 90 degrees from the direction of observation was colored green. Scattering light from laser-excited plasma suggested to contribute to express voxel colors, because the color was changed to white as the polarization was rotated.

3.3 Improvement of the number of voxels

In order to increase the number of voxels per unit time, we tried to increase the repetition rate of a laser source, and to apply parallel generation of focal points using a CGH. Figure 4 shows aerial line images drawn by femtosecond lasers with repetition rates of 1 kHz and 10 kHz, respectively. These images were drawn with a pulse energy of 285 μJ and an exposure time of 1/13 s. Voxel density of the image drawn by using 10 kHz femtosecond laser was higher than the image with 1 kHz, because the repetition rate directly contribute to increase the number of voxels per unit time.

Figure 5(a) shows the CGH applied to the drawn graphics. By displaying it on the LCOS-SLM, grayscale values of 0 to 255 can be assigned to the light values with a phase modulation of 0 to 2 π. This CGH controls the light to form four focal points as shown in Fig. 5(b). Figure 5(c)(d) shows volumetric Lissajous figures drawn with a single focal point and four parallel focal points generated in parallel by the CGH, respectively. These graphics were generated in a Xe-filled glass cell and captured in form of movies at 20 fps. These results indicate that the parallel

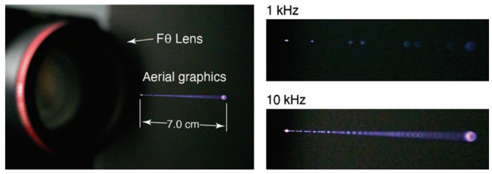

Fig. 4 Line images drawn by 1 kHz and 10 kHz femtosecond lasers.

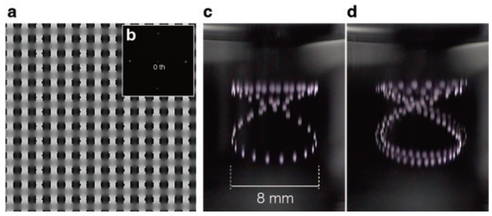

Fig. 5 (a) CGH and (b) reconstructed focal points. Volumetric images drawn with (c) a single and (d) four focal points.

focal points generate a graphics in which voxels are filled at a higher density compared to the single focal point for a graphics generated in one frame.

4 Conclusions

We introduced coloring methods of femtosecond-laser-excited voxel for a color volumetric display. DSS enabled emission color extraction from voxels, and produced a color volumetric image which have no boundaries in physical space. In addition, we observed that scattering of laser-excited aerial plasma capable of contributing to change the voxel color. In addition, we have demonstrated that improvement of the number of voxels by increasing the repetition rates of a light source and applying the parallel generated focal points with CGH.

Acknowledgements

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