Multimodal Acoustic Trapping Display

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Keywords: Acoustic levitation, Volumetric displays, Haptics sensation, Parametric audio.

ABSTRACT

The Multimodal Acoustic Trapping Display (MATD) makes use of ultrasound to trap, quickly move and color a particle, to create volumetric shapes in mid-air. Using the pressure delivered by ultrasound, the MATD can also create high-pressure points that our hands can feel and induce air vibrations that create audible sound.

1 INTRODUCTION

Volumetric displays are one of the three 3D display families that can create 3D images without the need for special eyewear. They are based on light-scattering or -emitting points and offer unconstrained visibility anywhere around the display. Some of those volumetric displays operate in mid-air with no barrier between user and image (referred to as free-space displays) and can be created using plasma [1, 2], mirage [3] and scanning particles using light [4] and electromagnetic field [5]. However, none of these approaches rely on operating principles that can produce tactile and audio content as well.

In this paper, we present a Multimodal Acoustic Trapping Display (MATD): a particle-scanning-based volumetric display using acoustic levitation that can simultaneously deliver tactile and audio content [6]. Acoustic levitation displays reported before the MATD [7-11] have only demonstrated control of a reduced number of points at reduced speeds and do not involve touch or audible sound. By contrast, our MATD makes use of ultrasound to trap, quickly move and color a small particle in mid-air, to create colored volumetric shapes visible to our naked eyes. Making use of the pressure delivered by the ultrasound waves, the MATD can also create points of high pressure that our bare hands can feel and induce air vibrations that create audible sound. In other words, the MATD can create multimodal 3D content that we can see, feel and hear using acoustophoresis as the single operating principle.

2 Operating Principles of the MATD

2.1 System Overview

The MATD system is composed of two opposed arrays of 16 × 16 transducers, aligned on top of each other and with a separation of 24 cm (Fig. 1). We used Murata MA40S4S transducers (40 kHz, 1 cm diameter) for the two arrays and high-intensity RGB LEDs (OptoSupply, OSTCWBTHC1S) to illuminate a levitated particle. A Waveshare CoreEP4CE6 FPGA board was used to receive updates from the host PC (3D position, RGB color, phase and amplitude) and individually controls the ultrasound transducers and the illumination LEDs.

The MATD computes single twin traps (for levitation) or focusing points (for haptics) at a hardware level using the FPGA. This enables position and amplitude updates of the trap at a rate limited only by the transducer frequency (i.e. 40 kHz). This computation of the traps provides controlled and fast levitation of our scanning particle (1-mm-radius, EPS bead) and is synchronized with the RGB LEDs, allowing the creation of a POV (persistence of vision) display with accurate control of the perceived color. Mid-air tactile feedback at controlled locations is created by using a secondary focusing trap and custom multiplexing policy. The system can also produce audio sound from the ultrasound transducers using amplitude demodulation in mid-air.

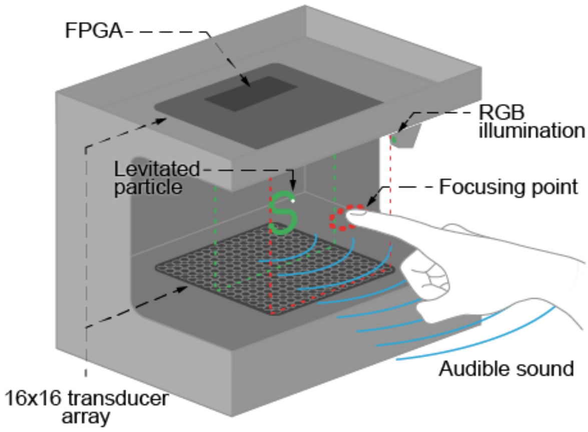

Fig. 1 The MATD setup [6].

2.2 Driving Parameters

Transducer Operation: The transducers were driven using a 12 Vpp square wave signal at 40 kHz, producing a sinusoidal output owing to their narrowband response. Phase delays were implemented by temporal shifting of the 40-kHz square wave, whereas amplitude control was achieved by reducing the duty cycle of the square wave. The complex amplitude of the transducers do not vary linearly with duty cycle. The relationship between the duty cycle and the amplitude of the transducers (A_t) can be represented as:

$$A_t = \sqrt{\sin^2\left(\frac{duty}{100}\pi\right)} \qquad (1)$$

We stored this function as a look-up table in the FPGA for efficient computation of the updates at the required rate (40 kHz). This resulted in a modulator providing 64 levels of phase (resolution of π/32 rad) and 33 levels of amplitude resolution.

Computation of traps: The computation of the focus points and twin levitation traps is embedded into the FPGA. For a focus point at position $\boldsymbol{p}$ and with phase ϕ_p, the phase of each transducer (ϕ_t) was discretized as follows:

$$\phi_t = \left(-\frac{32}{\pi}k|\boldsymbol{p} - \boldsymbol{p_t}| + \phi_p\right) \bmod 64. \qquad (2)$$

where k represents the wave number for the frequency used, $\boldsymbol{p_t}$ represents the position of each transducer. The twin traps were computed by combining a high-intensity focus point and a levitation signature [11]. The levitation signature was implemented by adding a phase delay of π rad to the transducers in the top array, as used in [10].

Illumination control: We used one illumination module equipped with the high-intensity RGB LEDs, which was placed on the top right corner of our MATD prototype. Intensity of the LEDs were controlled by the FPGA using pulse width modulation (PWM) with the gamma correction.

2.3 Content Creation

Visual content: Human eyes can integrate different light stimuli under a single percept (that is, a single shape or geometry) during short periods of time (0.1 s is usually accepted as a conservative estimation, even in bright environments [12]), and thus our particle needs to scan the content in less than this time.

Tactile content: Well differentiated tactile feedback was delivered using only a 25% duty cycle for tactile content. Thus, 75% of the cycles could still be used to position the primary trap, and the tactile content resulted in minimum loss of scanning speed. For our experiments, we chose a modulation frequency of 250 Hz. We use both amplitude and spatio-temporal modulations of the focusing point to create tactile stimuli. The 10-kHz update rate for tactile stimulation is sufficient for spatio-temporal multiplexing strategies to maximize the fidelity of mid-air tactile content [13].

Audio content: Audible sound is created by ultrasound demodulation using upper-sideband amplitude modulation [14] of the traps. Our sampling at 40 kHz encodes most of the auditive spectrum (44.1 kHz), and the high-power transducer array produces audible sound even for a relatively small modulation index (i.e. m = 0.2) while still modulating particle positions and tactile points at the 40-kHz rate. For simultaneous auditive and tactile stimulation, we combine the 40-kHz multifrequency audio signal with the tactile modulation signal (250 Hz).

3 RESULTS

3.1 Performance of the MATD

Our linear speed tests revealed high scanning speeds, much higher than those of optical [4] or acoustic [10] setups demonstrated until now. The system demonstrates particle speeds of up to 8.75 m/s and 3.75 m/s in the vertical and horizontal directions when providing only visual content.

We performed 3D pressure measurements and confirmed that the focusing tactile points have sound pressure levels greater than 150 dB, which is strong enough to provide tactile stimulation. In addition, our audio measurements revealed accurate representation of the input signal with some degradation due to harmonics.

3.2 Multimodal Content

Figure 2 shows examples of 2D (Figs. 2a and 2b) and 3D (Fig. 2c) vector content that the MATD can create in mid-air. These simple shapes can be scanned in 0.1 s and thus can be seen as solid POV images for human eyes, even under conventional indoor illumination conditions. Our volumetric content showed no substantial flicker and good color reproduction, independently of the viewer's location. Figure 2d shows three examples of color tests performed with vector images (numbers, as in a seven-segment display), showing good color saturation. Brighter images can be obtained by adding extra illumination modules or more powerful LEDs. Also the examples of visual content in Fig. 2d were created with simultaneous audible sounds of 60 dB (voice pronouncing the numbers).

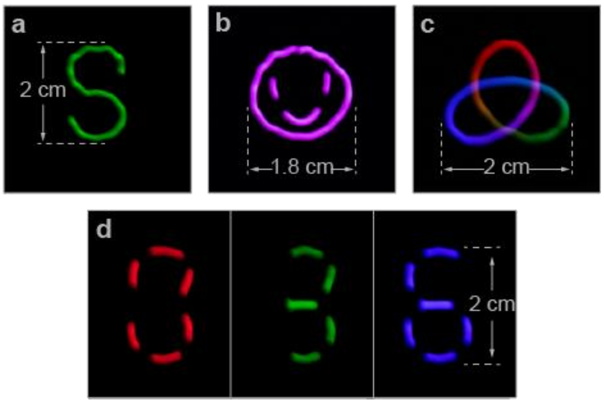

Fig. 2 Example of POV images [6].

Figure 3 shows more complicated visual content: 2D rasterized content (Fig. 3a), 3D vector content (Fig. 3b) and 3D rasterized content (Fig. 3c). These shapes cannot be scanned in the POV time (0.1 s) by the current MATD system. Therefore, these photos were taken with long exposure time (20 s). The 2D rasterized image in Fig. 3a were created with simultaneous tactile stimuli, which was strong enough to be felt by our hands.

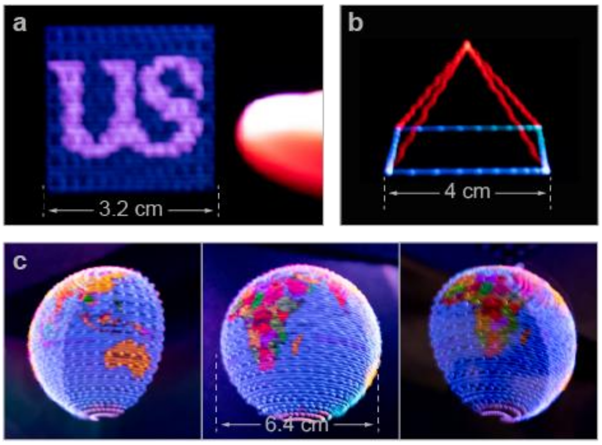

Fig. 3 Long-exposure shots of visual content [6].

4 DISCUSSION

Our instantiation of the MATD presented here was created using low-cost, commercially available components, making it easy to reproduce but also introducing limitations. Our tests were performed at a transducer voltage allowing continued usage (12 Vpp). Tests at higher voltages (15 Vpp, duration <1 h) indicate that increasing the transducer power can result in better performance parameters (for example, maximum horizontal speed of 4 m/s) and more complex content. Similarly, transducers operating at higher frequencies (that is, 80 kHz) can also improve audio quality and, combined with a reduced transducer pitch, would improve the spatial resolution of the levitation traps (more accurate paths of the scanning particle).

The MATD demonstrated the possibility to manipulate particles by retaining them in a dynamic equilibrium (rather than a static one, as most other levitation approaches), enabling the high accelerations and speeds observed. The use of models that accurately predict the dynamics of the particle (that is, in terms of acoustic forces, drag, gravity and centrifugal forces, but also considering interference from secondary traps and transient effects in the transducer phase updates) would allow better exploitation of the observed maximum speeds and accelerations. Also, as demonstrated in our latest paper [15], a high-speed multi-point algorithm makes it possible to manipulate several traps quickly without time multiplexing, enabling to create larger and more complex content.

5 CONCLUSION

Our study demonstrates an approach to creating volumetric POV displays with simultaneous delivery of auditive and tactile feedback and with capabilities that exceed those of alternative optical approaches [4]. Polarization-based photophoretic approaches [16] could match the potential for particle manipulation (that is, speeds and accelerations) demonstrated in this study, but they would still be unable to include sound and touch. The demonstrated MATD prototype hence brings us closer to volumetric displays providing a full sensorial reproduction of virtual content. Beyond opening a new avenue for multimodal 3D displays, our device and techniques enable positioning and amplitude modulation of acoustic traps at the sound-field frequency rate (that is, 40 kHz).

ACKNOWLEDGEMENTS

We acknowledge funding from the EPSRC project EP/N014197/1 ‘User interaction with self-supporting free-form physical objects’, the EU FET-Open project Levitate (grant agreement number 737087), the Royal Academy of Engineering Chairs in Emerging Technology Scheme (CiET1718/14), the Rutherford fellowship scheme, JSPS through Grant-in-Aid number 18J01002 and the Kenjiro Takayanagi Foundation.

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