

Aerial Interaction with Holograms of Insensible Frequency towards generating Audio, Visual, and Haptic feedback in the three-dimensional space

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Keywords: Hologram, Spot Audio, Aerial Image, Aerial Haptics

ABSTRACT

We introduce our case studies on aerial interaction methods that utilizes holograms of insensible frequency towards generating Audio, Visual, and Haptic contents in three-dimensional space. We employed Computer Generated Hologram for calculation and rendered with ultrasound by phased array and femtoseconds laser induced plasma by Spatial Light Modulators.

1. INTRODUCTION: Towards real world interactions and calm technologies

Audio, Visual, and Tactile information is the essential components of multimedia content and real-world interactions. In contrast to wearable solutions, non-wearable interactions have lower selectivity in contents delivery and are received by audiences who were not targeted by the media equipment. Conventional displays are almost omnidirectional, which is usually an undesirable feature in public places for personal communication and individually-fitted assistance. A technology to provide different multimedia information to different users is desired in ubiquitous computing (in other words, non-wearable computing). With such a technology, personalized contents delivery becomes possible and multimedia environments can be designed more freely. Continuous efforts have been made to this end, such as wave field synthesis, light field displays, aerial haptic display, ultrasound-based super-directional loudspeakers, and etc. In this article, we aimed at introducing our case studies [1] [2] [3] [4] of these areas as sequential researches.

In 1965, Ivan Sutherland stated that the ultimate display is a room that can control the existence of matter [5]. We envision that digital resources should be accessible as freely as non-digital resources (e.g., physical objects) at the goal of IoT technologies. We also believe that non-digital material should be as malleable as digital material in digital resources (e.g., data in computers). To realize that concept of the room, insensible medium that connects the matters and environmental computational resources is necessary for the human computer interaction. Thus, we consider forming the insensible hologram as computational medium.

In several case studies, we have utilized CGH, wave

fronts (light and acoustic waves), and air to display information to users or to actuate objects around users to inform them. These fields of physical quantities rendered around users work as “Computational Ether” [15] that we could described it along the metaphor of “Ether” in classical physics. This Computational Ether suspends objects floated and also works as aerial media to render the graphical and haptic expressions. The method of handling field quantities by CGH is well known and matured, however this concepts framework enables us to clarify how to alter the physical environment by appropriate field design and to consider application areas [14].

We believe that field-oriented programmable matter is one means of realizing Calm Technology [6], i.e., a technology that informs us however does not demand our focus of attention. Mark Weiser suggested the vision of Calm Technology in 1996. Some two decades on, our daily lives are surrounded by computers [7]. As Weiser pointed out, calmness is a fundamental challenge for all technological design for the next 50 years; we are now facing issues related to calmness.

As he pointed out, a vision designed with an appropriate combination of scientific aspects, technology, design, and implementation can drive us toward a solution for calmness, i.e., awareness of ubiquitous computers [7]. We believe this problem can be solved if ubiquitous or pervasive computers can alter the real world to be “programmable” by hidden and separated field generators that activate invisible medium. To implement them, we noticed computational generated field on air that is rendered by separated generators. In this case, the technology itself (digital resources or machines) is hidden, and the actuation targets are mixed with other non-digital objects. These are not distinguishable until they are actuated or activated, and therefore do not require our attention unnecessarily. Then we considered the air is one of most suitable medium to utilize for calmness. We have utilized invisible infrared laser and inaudible ultrasound to generate holograms for calmness interactions that connect computational resources and activated matters without attention.

2. Related Work: Volumetric Displays and Screens, Aerial Haptic Feedback and Directional Audio

The case studies that we raised these articles [2] [3] [4] are generally categorized three dimensional volumetric displays. Studies directed toward controlling the spatial position of an active screen and display are also being actively pursued in display researches. There are two kinds of the studies; one aims to achieve multi-perspective 3D image and the other aims to realize deformation of planner screens for haptic and/or other purposes. Multi-perspective 3D display is a popular topic in computational display areas. [8] constructs 3D images with a rotated mirror and projection. On the other hand, there are researches that focus on the dynamic deformable screen and display. For example, the deformable actuated screen "Project FEELEX" [9] constructs 3D forms on the screen surface using an actuator array set under the screen. Inform [10] has proposed an interactive deformable screen, called that handles and/or interacts with other objects. A noncontact-actuated deformable screen [11] employs an ultrasonic-phased array to deform a colloidal screen. While there is a 3D solution [12] that uses a plasma 3D volumetric display. Our researches are based on these conventional studies and we aimed not only to show 3D image but to mix 3D interaction with user's environment.

Case studies [1] [4] are generally categorized haptic display and spatial audio. Recently, ultrasound has been used to produce audio source and haptic feedback in air, by using the principle of acoustic radiation pressure, which is a nonlinear effect where high-intensity ultrasound presses the object surface and this nonlinear effect is also applied to generate audible sound in the beams of ultrasonic. The phased-array focusing technique is used to achieve high intensity at the focal point [13, 14]. Generating multiple focal points simultaneously is possible [15, 16]. We utilized this effect to generate the haptic feedback and aerial point sound sources.

3. Principle

3.1 Computer Generated Hologram

We basically utilize computer generated hologram to generate the computational acoustic and light fields however note that. Because of the limitation on laser intensity endurance of SLM, we combine SLM, Galvano mirror, and varifocal lens to generate images in laser applications and because of the limitation in resolution of phased array, we combined holographic control and spatial control to generate computational acoustic field. The spatial phase control of light and acoustic field enables the focusing position to be controlled along both the lateral (X and Y) and axial (Z) directions. The complex amplitude (CA) of the reconstruction from the computer-generated hologram (CGH) U_r is given by the Fourier transform of the designed CGH pattern U_h :

$$U_r(v_x, v_y) = \iint U_h(x, y) \exp[-i2\pi(xv_x + yv_y)] dx dy$$

$$= a_r(v_x, v_y) \exp[i\varphi_r(v_x, v_y)] \quad (1)$$

$$U_h(x, y) = a_h(x, y) \exp[i\varphi_h(x, y)] \quad (2)$$

where a_h and φ_h are the amplitude and phase of the

hologram plane displayed on the SLM or Phased Array, respectively. In the experiment, a_h is constant because the light irradiation on the CGH is considered to be plane wave with a uniform intensity distribution and also it is constant on the acoustic field because amplitude of all transducers on ultrasonic phased array is same value. φ_h is obtained by hologram calculation algorithm, whereas a_r and φ_r are the amplitude and phase of the reconstruction plane, respectively.

The spatial intensity distribution of the reconstruction is actually observed as $|U_r|^2 = a_r^2$. To control the focusing position along the lateral (X and Y) direction, the CGH is designed based on a superposition of CAs of blazed gratings with a variety of azimuth angles. If the reconstruction has N -multiple focusing spots, the CGH includes N -blazed gratings. To control the focusing position along the axial (Z) direction, a phase Fresnel lens pattern $\varphi_p(x, y) = k(x^2 + y^2)/2f$ with a focal length f is simply added to φ_h , where $k = 2\pi/\lambda$ is a wave number.

In this case, the spatial resolution of the SLM and the interval length of transducers on Phased Array determines the minimum focal length of each computational field respectively. In conventional study [13], ultrasonic phased array was controlled to render a single point in X and Y by given (1) and Z position is decided by this CGH pattern (phase Fresnel lens pattern) on ultrasonic phased array.

3.2 Haptic Images

Haptic images on cross field project [4] are given by a combination of an SLM image and galvano mirror and radiation pressure of ultrasonic focal points. Haptic image H_i is the summation of the time series of the focal points, that is,

$$H_i = \sum U_r(v_x, v_y) \times i_l \times t_l + \sum f_p(x, y, z) \times p \times t_a \quad (3)$$

where U_r represents the laser focal points given by (1), t_l is time duration, i_l is laser intensity, f_p is the radiation pressure of ultrasonic focal points [13], p is the acoustic pressure, and t_a is the time duration. And also this H_i can be modulated in audible frequency [1] and this method enables to realize various haptic textures in the air.

Then, we introduce several case studies in next section. Common ground of these studies is employing "air" to generate stimulation for users [18].

4. Case Studies

4.1 Audio Applications

This is the project named Holographic Whisper [1] and systems are shown in Figure 1(a). In this case study, we explored the methods of spatial audio rendering using ultrasound. An ultrasonic phased array generates one or more focal points in air, and they act as point sources of audible sound when the ultrasound waves are modulated. Our sound-point loudspeaker has two major advantages over conventional ultrasound-based sound-beam (super-directional) loudspeakers. The higher audience selectivity means that our sound-point

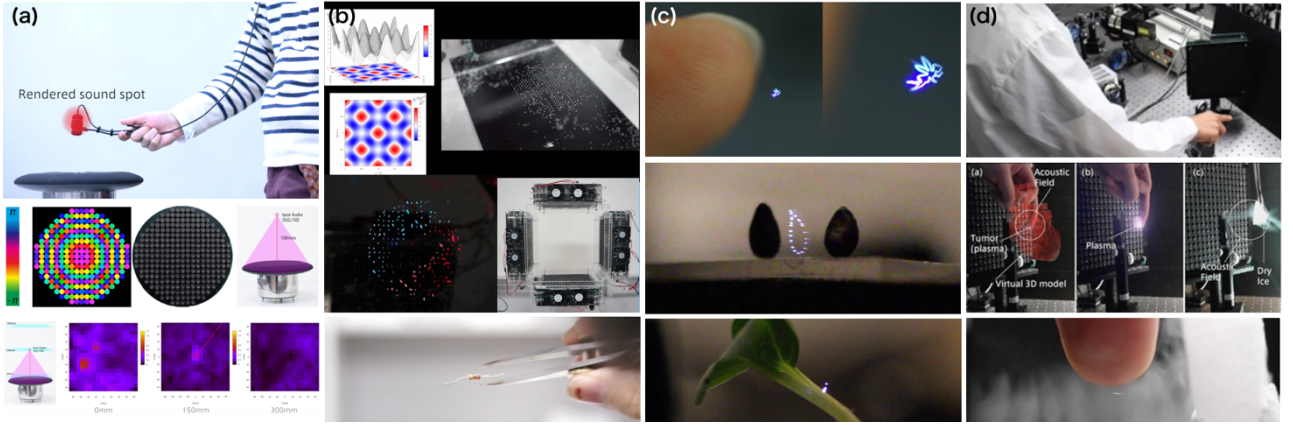


Figure 1. Appearance and overview of case studies (a) Holographic Whisper [1]: rendering spot audio by ultrasonic holograms. (b) Pixie Dust [3]: rendering physical graphics by ultrasonic holograms. (c) Fairy Lights in Femtoseconds [2]: rendering plasma graphics by laser induced plasma by CGH holograms and Galvano mirror. (d) Cross-Field Haptics [4]: aerial haptic feedback by ultrasonic holograms and laser induced plasma by CGH holograms and Galvano mirror.

loudspeaker can deliver sound to the ears of the target person, whereas a sound-beam loudspeaker delivers sound to not only the target person but also other persons standing in the same direction. The other advantage is lower exposure to ultrasound; while an audible sound beam travels along an ultrasonic beam in a sound-beam loudspeaker, audible sound can be heard along the direction perpendicular to the ultrasonic beam in our sound-point loudspeaker.

4.2 Graphics by Computational Acoustic Fields

This is the project named Pixie Dust [3] and systems are shown in Figure 1(b). We have utilized ultrasonic phased array and generate acoustic fields in three dimensionally positions. In conventional research on acoustic levitation, small objects are trapped in the acoustic beams of standing waves. We expanded this method by changing the distribution of the acoustic-potential field (APF). Acoustic-Potential Field is generated by four ultrasonic phased arrays [19]. Using this technique, we could generate the graphics using levitated small objects. Our approach made available many expressions, such as the expression by materials and non-digital appearance. The spatial resolution of the position is 0.5 mm. Particles move at up to 72 cm/s. The allowable density of the material can be up to 7 g/cm³. For this study, we use three options of APF: 2D grid, high-speed movement, and combination with motion capture.

These are used to realize floating screen or mid-air raster graphics, mid-air vector graphics, and interaction with levitated objects. And also, it can be combined with haptic feedback [4] with aerial tangible images by levitated materials.

4.3 Graphics by Computational Light Fields

This is the project named Fairy Lights in Femtoseconds [2] and systems are shown in Figure 1(c). We have utilized femtoseconds laser source and spatial light modulator to generate laser induced plasma by laser light fields in three dimensionally positions. This is a display method of

rendering aerial and volumetric graphics using femtosecond lasers. A high-intensity laser excites physical matter to emit light at an arbitrary three-dimensional position. In this project, we employed two methods of rendering graphics with a femtosecond laser in air: producing holograms using spatial light modulation technology and scanning of a laser beam by a Galvano mirror.

The holograms and workspace of the system proposed here occupy a volume of up to 1 cm³; however, this size is scalable depending on the optical devices and their setup. We tested two laser sources: an adjustable (30–100fs) laser that projects up to 1,000 pulses/s at an energy of up to 7mJ/pulse and a 269fs laser that projects up to 200,000 pulses/s at an energy of up to 50μJ/pulse. We confirmed that the spatiotemporal resolution of volumetric displays implemented using these laser sources is 4,000 and 200,000 dots/s, respectively.

In this project, we proposed design methods of “tangible 3D images” by utilizing femtosecond laser induced plasma. The spatial resolution of voxels is 100μm interval and participants in this study states that displayed object cannot be distinguished from physical solid materials.

4.4 Haptic and Cross-Field Applications

This is the project named Cross-field aerial haptics [4] and systems are shown in Figure 1(d). In this project, we presented a new method of rendering aerial haptic images that uses femtosecond-laser light fields and ultrasonic acoustic fields. In conventional research, a single physical quantity has been used to render aerial haptic images. In contrast, this method combined multiple fields (light and acoustic fields) at the same time. While these fields have no direct interference, combining them provides benefits such as multi-resolution haptic images and a synergistic effect on haptic perception. We conducted user studies with laser haptics and ultrasonic haptics separately and tested their superposition. The

results showed that the acoustic field affects the tactile perception of the laser haptics. We explored augmented reality/virtual reality (AR/VR) applications such as providing haptic feedback of the combination of these two methods. This project is aimed at combining these two projects from the viewpoint of haptic feedback and how to combine them as unified system.

5. General Discussions and Future Work

Spatiotemporal Resolution on each system are determined by its hologram generators. The key factor of spatiotemporal resolution is refresh rate and endurance of spatial light modulators for our laser systems. These two factors decide the limitation of parallel access to aerial voxels. To reduce the other optical components such as Galvano mirror and varifocal lens, we have to increase the refresh rate of SLM in our systems. For our acoustic systems, the key factor is size of transducer arrays. Transducer size itself decided by the wave length of ultrasound. To achieve high resolution of hologram image, we have to increase the size of transducer arrays.

One of the drawbacks of noncontact display and actuation is that the efficiency of energy transmission is lower than that of conventional contact-based methods (e.g., led wired from electric circuit, motor). In spite of this, the absence of bulky mechanical systems in the workspace is a large advantage of the noncontact actuation technologies from the viewpoint of calmness.

6. Conclusions

In this article, we introduce our case studies on the aerial interaction method that utilizes holograms of insensible frequency. We introduced the results of our research group such as case studies; aerial haptic interaction, aerial touch displays, 3D manipulation of objects, new material expression displays, and point audio source. The resulting system can be applied to display technologies such as Computer Graphics, Entertainment Computing, and Human Interfaces. We believe these technologies stimulate display researches

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