

Pixels towards Pixies: Post-Multimedia interactions with Air-Based Media

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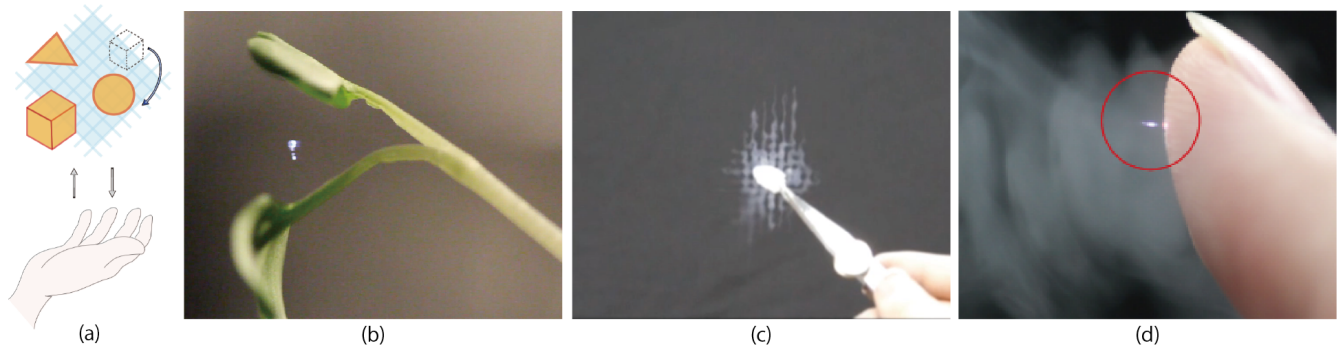


Figure 1. (a) Interaction concept of Computational Ether [1], (b) Laser Plasma Graphics induced by Femtosecond laser [2], (c) Acoustic Field [3] rendered and visualized by dry ice (d) tactile feedback rendered by both acoustic and light fields [4]

Abstract

Towards post multimedia interactions, we envision real world oriented interactions with Computational Generated Fields on Air; we called this interaction concept as “Computational Ether”. Along this concept we have conducted studies to propose a method for realizing new physical interactions that expands malleability of non-digital material towards programmable matter in the real world [1]. Our method utilizes light field [2] and acoustic field [3] these are calculated, generated, and controlled by computers. By applying such computational fields of quantities and physical phenomena around the holographic field, we transformed ordinary air into interactive visual media [2], haptic media [4], and actuators [3]. To implement these interactive media, we employed Computer Generated Hologram and rendered with ultrasound generated by acoustic phased array and laser induced plasma generated by femtosecond laser sources with Spatial Light Modulators. In this paper, we introduce 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 so on. Finally, we discuss the advantages and limitations of our method. We believe these technologies stimulate display researches from 2D pixels on the surface towards 3D pixies flying in the air.

Author Keywords

Human Computer Interaction; Computer Graphics; Femtosecond Laser; Haptic Interface; Tangible Interaction; CGH

1. Introduction: Computational Ether

Towards Real World Interactions: 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 the concept of the room that Ivan Sutherland suggested, invisible medium that connects the matters and environmental computational resources is necessary for the human computer interaction. Thus we consider to control the “air” as computational medium.

In conventional 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” that we could describe 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.

Calm Technologies: 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 or 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: Programmable Matter

Visions: Programmable matters - controlling objects in the real world is now popular topic in the computer graphics, display, and human-computer interaction communities. Various ideas and

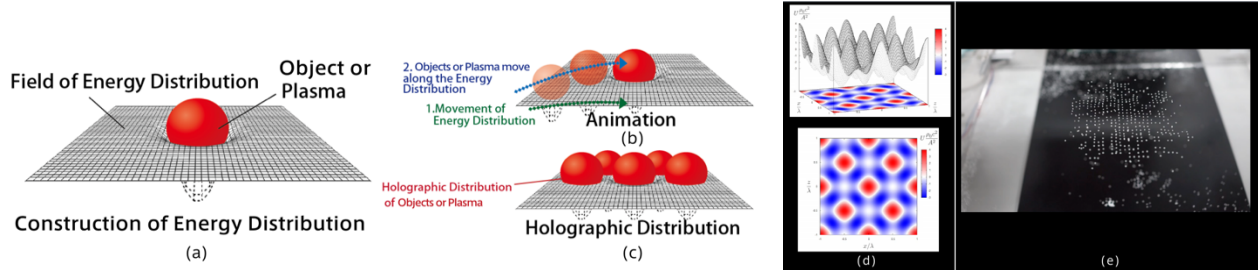


Figure 2. Concept of Computational Ether (Field Distribution) (a) construction of energy distribution, (b) animation (c) holographic distribution (d) simulated results (e) rendered result [3]

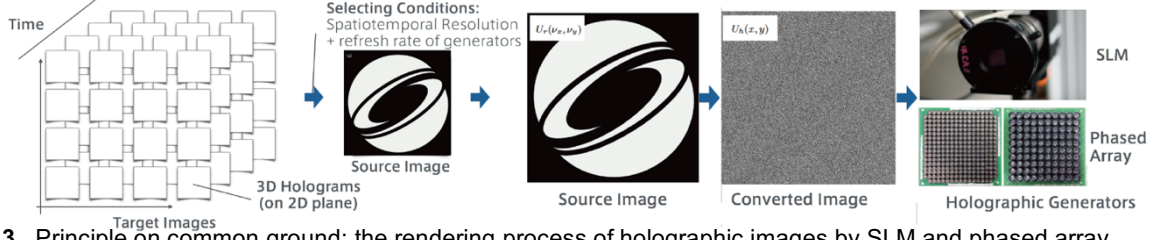


Figure 3. Principle on common ground: the rendering process of holographic images by SLM and phased array.

visions to organize and realize this concept have been proposed – e.g., programmable matter [8], radical atoms [9], and actuation interfaces [10]. These proposals focus on controlling real objects through a computer and generating physically programmable material. These concepts will play very important roles in future interactive environments because they expand the range of computer applications from “painted bits” to the real world [11]. Two methods are currently available to control objects in the real world. In one, objects actuate themselves, whereas they are actuated by their surroundings in the other. The latter method is divided into two types of actuation: contact and noncontact. We address the noncontact approach by utilizing invisible resources and activate air medium (concept is shown in Figure 2).

Volumetric displays and screens: The case studies that we raised in this 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. [12] 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” [13] constructs 3D forms on the screen surface using an actuator array set under the screen. Inform [14] has proposed an interactive deformable screen, called that handles and/or interacts with other objects. A noncontactly-actuated deformable screen [15] employs an ultrasonic-phased array to deform a colloidal screen. While there is a 3D solution [16] 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.

3. Principle on Common Ground

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, galbano 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 :

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

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

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

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 $\phi_p(x, y) = k(x^2 + y^2)/2f$ 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 [17], ultrasonic phased array was controlled to render a single point in X and Y by given (1) and Z position is decided by this phase Fresnel lens pattern on ultrasonic phased array.

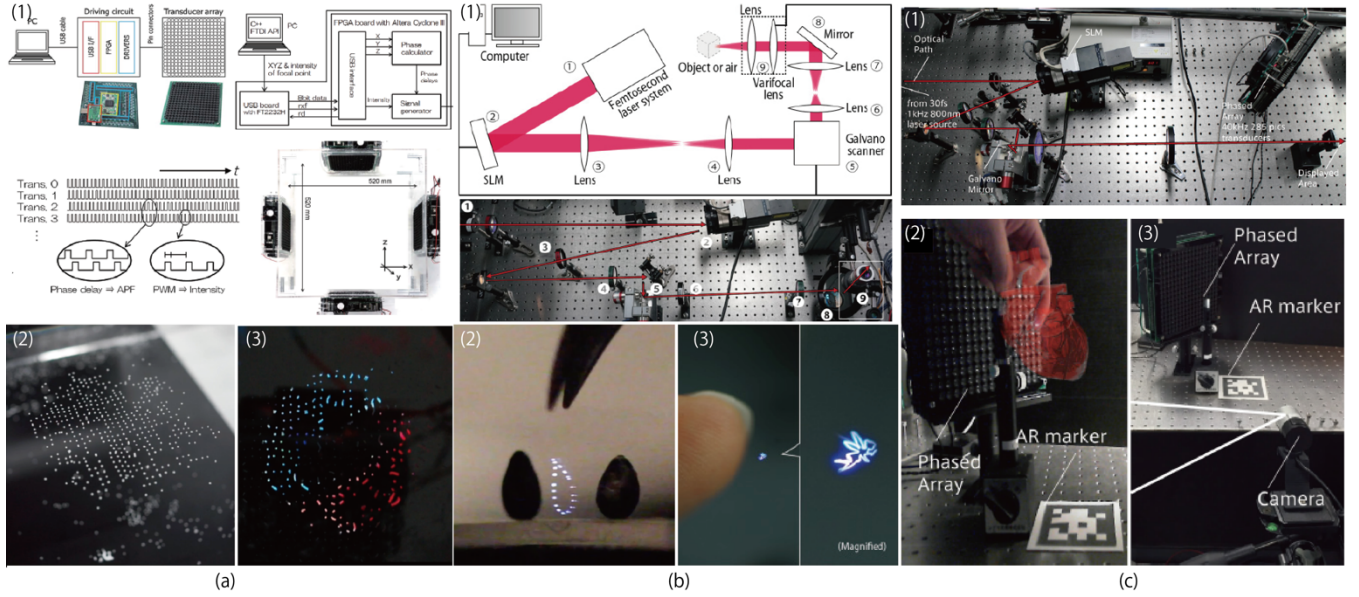


Figure 4. System and Applications (a) Pixie Dust [3] (b) Fairy Lights in Femtoseconds [2] (c) Cross-Field Haptics [4]

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 [19], p is the acoustic pressure, and t_a is the time duration.

4. Case Studies

In this section we introduce several case studies. Common ground of these studies are employing “air” to generate stimulation towards user by implementing Computational Ether concept shown in Figure 4.

Graphics by Computational Acoustic Fields: This is the project named Pixie Dust [3] and systems are shown in Figure 4(a-1). 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 (Figure 4(a-2,3)). Our approach made available many expressions, such as the expression by materials and non-digital appearance. These kinds of expressions are used in many applications, and we aim to combine them with digital controllability. In the current system, multiple particles are levitated together at 4.25-mm intervals. 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 [19]

with aerial tangible images by levitated materials.

Graphics by Computational Light Fields: This is the project named Fairy Lights in Femtoseconds [2] and systems are shown in Figure 4(b-1). 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. Popular applications can thus be explored, especially because plasma induced by a femtosecond laser is less harmful than that generated by a nanosecond laser. There are 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 (Figure 4(b-2,3)).

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 can not be distinguished from physical solid materials.

Haptic and Cross-Field Applications: This is the project named Cross-field aerial haptics [4] and systems are shown in Figure 4(c-1). 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 (Figure 4(c-2,3)) such as providing haptic feedback of the combination of these two methods. This project is aimed at combining these two project 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.

Our concept of Computational Ether covers noncontact and display technologies that conceal the generators from human sight and increase the programmability of the actuation of matter. We believe this is a worthy contribution the realization of Calm Technologies. We believe field-oriented programmable matter is a useful concept in the development of Calm Technologies from the aspect of interface selectivity. We employed non-digital materials to bring about actuation [4]. These are examples in which non-digital materials turn into programmable matter. 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 described real world oriented interactions with computational generated field of quantities on air towards post multimedia interactions and we introduced interaction concept as "Computational Ether". Along this concept we have conducted computer generated hologram research to propose a method for realizing new physical interactions that expands their malleability towards programmable matter in the real world. As case studies we raised several implementations by applying such computational fields of quantities and physical phenomena around the holographic field. 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 so on. The resulting system can be applied to display technologies such as Computer Graphics, Entertainment Computing, and Human Interfaces. Finally, we discuss the advantages and limitations of our method. we employed Computer Generated Holograms rendered with ultrasound generated by acoustic phased array and laser induced plasma generated by femtosecond laser sources, Spatial Light Modulators, and optical components. We believe these technologies stimulate display researches from 2D pixels on the surface towards 3D pixies like programmable matter.

7. References

- [1] Ochiai, Y. Graphics by Computational Acoustic Fields, Doctoral Dissertation, The University of Tokyo, 2015.
- [2] Ochiai, Y., Kumagai, K., Hoshi, T., Rekimoto, J., Hasegawa, S., and Hayasaki, Y. Fairy Lights in Femtoseconds: Aerial and Volumetric Graphics Rendered by Focused Femtosecond Laser Combined with Computational Holographic Fields. *ACM Trans. Graph.* 35, 2, Article 17 (February 2016), 14 pages, 2016.
- [3] Ochiai, Y., Hoshi, T., and Rekimoto, J. Pixie dust: graphics generated by levitated and animated objects in computational acoustic-potential field. *ACM Trans. Graph.* 33, 4, Article 85 (July 2014), 13 pages, 2014.
- [4] Ochiai, Y., Kumagai, K., Hoshi, T., Rekimoto, J., Hasegawa, S., and Hayasaki, Y. Cross-Field Aerial Haptics: Rendering Haptic Feedback in Air with Light and Acoustic Fields, In *Proc of CHI 2016*, CHI'16, May 07-12, 2016, San Jose, CA, USA, 2016.
- [5] Sutherland, I. E. The ultimate display. *Proc. IFIP Congress* (1965), 506-508. 1965.
- [6] Weiser, M. and Brown, J.S. The coming age of calm technology. *Beyond Calculation* (1997), 75-85. 1997.
- [7] Weiser, M. The Computer for the 21st Century. *Scientific American* 265, 3 (1991), 66-75. 1991.
- [8] Goldstein, S.C., Campbell, J.D., and Mowry, T.C. Programmable matter. *Computer* 38, 6 (2005), 99-101. 2005.
- [9] Ishii, H., Lakatos, D., Bonanni, L., and Labrune, J.B. Radical atoms: Beyond tangible bits, toward transformable materials. *Interactions* 19, 1 (2012), 38-51. 2012.
- [10] Poupyrev, I., Nashida, T., and Okabe, M. Actuation and tangible user interfaces: The Vaucanson duck, robots, and shape displays. *Proc. TEI, ACM* (2007), 205-212. 2007
- [11] Ishii, H. and Ullmar, B. Tangible bits: Towards seamless interfaces between people, bits and atoms. *Proc. CHI, ACM* (1997), 234-241. 1997
- [12] Jones, A., McDowall, I., Yamada, H., Bolas, M., Debevec, P. Rendering for an interactive 360° light field display. *ACM Trans. Graph.* 26, 3 (July). 2007.
- [13] Iwata, H., Yano, H., Nakaizumi, F., and Kawamura, R. Project FEELEX: Adding haptic surface to graphics. *Proc. SIGGRAPH, ACM* (2001), 469-476. 2001.
- [14] Follmer, S., Leithinger, D., Olwal, A., Hogge, A., and Ishii, H. inFORM: Dynamic physical affordances and constraints through shape and object actuation, *Proc. UIST, ACM* (2013), 417-426. 2013.
- [15] Ochiai, Y., Oyama, A., Hoshi, T., and Rekimoto, J. Poppable display: A display which enables people to interact with popping, breaking, and tearing, *Proc. GCCE, IEEE* (2013), 124-128. 2013.
- [16] Kimura, H., Uchiyama, T., and Yoshikawa, H. 2006. Laser produced 3D display in the air. In *ACM SIGGRAPH 2006 Emerging Technologies*, ACM, New York, NY, USA, SIGGRAPH '06. 2006.
- [17] Hoshi, T., Takahashi, M., Iwamoto, T., and Shinoda, H. Noncontact tactile display based on radiation pressure of airborne ultrasound. *IEEE Transactions on Haptics* 3, 3, 155-165, 2010