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Improving photophoretic trap volumetric displays [Invited]

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Since the introduction of optical trap displays in 2018, there has been significant interest in further developing this technology. In an effort to channel interest in the most productive directions, this work seeks to illuminate those areas that, in the authors' opinion, are most critical to the ultimate success of optical trap displays as a platform for aerial 3D imaging. These areas include trapping, scanning, scaling, robustness, safety, and occlusion.

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1. INTRODUCTION

Optical trap displays (OTDs) like the photophoretic trap volumetric display, provide screenless, optical real images in free space [1]. OTDs are part of the point family [2] of 3D displays and, as such, they do not "clip" at the display boundary, they have constant resolution throughout the display volume, and they are capable of creating display geometries forbidden to wave (e.g., holographic) and ray (e.g., light field) displays. Because OTD displays have bandwidth requirements that are dependent on the number of voxels in the image, they can have much lower bandwidth requirements for sparse scenes than wave and ray displays of comparable size. Within the family of point displays, optical trap displays also stand out for their ability to project into image volumes that may be larger than the physical display itself.

Notwithstanding their manifold advantages, optical trap displays will require a number of improvements before they reach a scale at which they will be broadly useful. The authors' current goal is to achieve images with a linear dimension in excess of 20 cm [see Fig. 1(c)]. The authors' earliest efforts involved a single particle and a single beam (the beam serving as both the trap and the illumination beam) which were capable of creating 1 cm vector images, of low complexity that were rewritten at rates greater than 10 frames per second to provide persistence of vision [see Fig. 1(a)]. At the time of this writing, it is possible to create full-color vector images at video rates, or much more detailed rastered images at less than video rates, using multiple beams: one violet (405 nm) beam for trapping the particle and a set of red, green, and blue lasers to provide primaries for color mixing [Fig. 1(b)]. The respective intensities of these beams are 80 mW, 24.4 mW, 30.5 mW, and 15.89 mW. The presence of the visible 405 nm trapping beam will affect color mixing but has a limited perceptible affect because of the human eye sensitivity to near-UV wavelengths [3].

The current display capabilities are limited by the quality of the trap, the variation of the particles, and the speed of the scanning system. To achieve the target dimensions for next-generation OTD displays, and to make these displays suitable for the lay user, researchers will need to improve all of the following: trapping, scanning, scaling, robustness, and safety. This paper also briefly discusses each of potential impact of occlusion in OTDs and suggests possible early target applications for a scaled display.

2. TRAPPING

The quality of the optical trap within an OTD is critical to particle pickup, particle motion, and particle resilience to environmental conditions. The trap must be capable of picking up a particle in a robust, repeatable fashion. Currently, this is accomplished by scanning the trap through a reservoir of particles (though other methods are possible [4]). The trap must also be capable of holding the particle for long periods of time as it is moved through each image point over and over again as each frame is drawn. In the current OTD prototype, both pickup and hold are extremely variable with some particles holding in place for up to 15 h and withstanding up to 1 liter/s airflow [1] while many trap attempts fail to hold even a few seconds. This variability stems from the fact that we use aberration traps that have hundreds of trapping sites [5] of differing size and shape. This is helpful for "pickup" as most particles find a home; however,

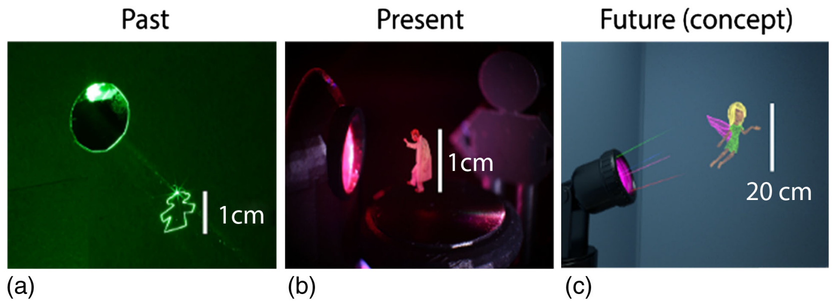


Fig. 1. (a) Photo of single-color, single-particle, vector, video rate, image 1 cm tall, circa 2016. (b) Photo of three-color, single-particle, line raster, *not* video rate image, 1 cm tall, circa 2018. (c) Conceptual image of three-color, multiple-particle, volume raster image, video rate, 20 cm tall.

the variation in sites also results in many trapping events being sub-optimal, and it is difficult to know whether the particle is located in a trap that possesses high contrast and has a morphology and dimension suited to the particle. The second source of variability is from the distribution of the particles themselves. The particle reservoir contains particles with sizes varying from less than 1 μm to tens of micrometers in diameter. The particle shapes also vary widely. This variety makes it possible to achieve good trapping results in the limit of large number of trials as many trap and particle parameters are represented, but high variability precludes repeatability. The characteristics of particles have a significant effect on the performance of the display. Moving from experimentation to optimization will require the isolation of a small, uniform set of traps and a uniform population of particles. Aberration will likely be replaced by other mechanisms for generating photophoretic optical traps, including holographic traps [6–8], phase contrast traps [9,10], and Poisson spots. To provide a uniform population of particles, the authors suggest the use of uniform coated microspheres [11,12] to replace black liquor. By testing one trap and one particle at a time, optimal pairings can be identified, and the effect of changes quantified. These tests could be facilitated by the use of a liquid crystal on silicon, which has already been used to create aberration traps [1] and could be updated to quickly provide a wide variety of trap types, serially, during testing.

3. SCANNING

Once an optimal particle and trap pair has been identified, attention should be given to improved scanning that will take advantage of the more robust individual trapping conditions. The current prototype uses galvanometric scanners and stage-mounted lenses to scan the space. However, it may be possible to replace these, all or in part, with solid-state scanning solutions that could increase total scan speed. Care must be taken to utilize a scanning solution that preserves the trap as it is scanned. Acousto-optics and electro-optics may be able to do this. It is less clear that liquid lenses or pneumatic lenses could do this without the need for active wavefront correction. Galvanometric scanning mirrors are, in general, achromatic, relatively fast (of the order of a few kilohertz bandwidth) [13], of large aperture (as large as 30 mm and above), and conservative of trap morphology as they scan. Given their advantages, rather than eliminate galvanometric scanners entirely, it might be best to use solid-state technologies, such as static gratings, to trap multiple particles simultaneously [14,15]. Then, with multiple particles in tow, an array of trapped particles can scan through a volume in a single pass, thereby increasing the sophistication of the images while simultaneously reducing the complexity of the scanning hardware. This approach suggests an alternative method for scaling the OTD image that does not require fast scanning as described below.

4. SCALING

In the current OTD prototype, a single particle is scanned through a complicated path [Fig. 2(a)]. The next-generation display may instead scan many particles through a simple path [Fig. 2(b)]. Similar approaches for multiple voxel generation have been shown previously [16,17]. As previously mentioned, changing to parallel optical beams will allow the reduction from dual-axis scanning to single-axis scanning. This reduces the complexity of the scanning while making it possible to create images with greater sophistication at video rates. Based on current maximum velocities [1], it should be possible to make images with a maximum linear dimension of 20 cm or 8 in. (before any further optimization of trap and hold) if every trapped particle is allowed to travel in a straight line during the frame. Given that aberration traps are inefficient, dividing their optical power over hundreds of trapping sites [5] (most of which are unused), we expect that the optical power freed by optimized traps should make it possible to trap a large number of particles in an array of identical trap sites [Fig. 2(e)] without greatly increasing the current optical power of the system. One straightforward method of duplicating traps is by the addition of a Damman or similar grating to the display output [14]. This simple modification is shown below in Fig. 2(b). Figure 2(c) shows a single particle system with an aberrated lens as the final optic and Fig. 2(d) shows a similar system with a rectangular amplitude grating added after the aberrated lens to create multiple traps—two of which hold a particle. Ideally, the display would have tens, hundreds, or thousands of particles, trapped and moving together. Multiple particle systems of up to several thousand particles have been demonstrated previously [14,15,18,19]. In such a scenario, the complexity of the display is shifted from the scanning sub-system to the illumination sub-system. The illumination sub-system will now be responsible for illuminating each particle independently of the others. The authors estimate that a practical upper bound on the number of simultaneously illuminated particles will probably be of the

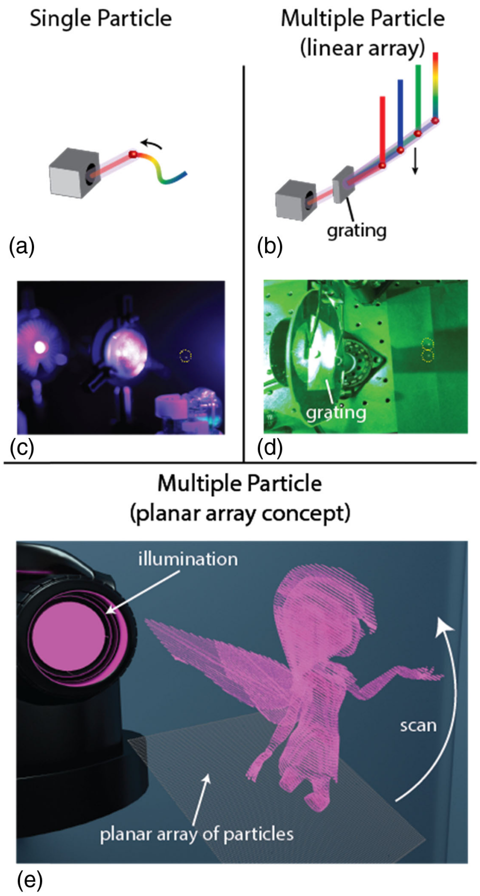


Fig. 2. Multi-particle scaling. (a) Single-particle display with a complex pathing and simple illumination. (b) Multiple-particle display with a simple path and complex illumination. (c) Lab result showing a single-particle system (image courtesy of Joel Rasmussen). (d) Lab result showing multiple suspended particles in a linear array from a single laser source. (e) Concept showing a planar array of suspended particles rastering a volume image, video rate refresh, large scanning volume.

order of millions of points assuming one-to-one pixel to particle mapping from commonly available spatial light modulator (SLM) products at the time of publication. Such numbers might still be considered sparse by 3D display standards [20]. Because the bandwidth of OTD displays scales with the number of particles, the bandwidth required for a one-million particle system could be below the 400 million pixels per second provided by each channel of a commodity graphics card [21,22]. This display bandwidth is several orders of magnitude below that required for a holographic display with the same view volume, making it possible to contemplate the use of OTDs for real-time applications, such as face-to-face telepresence. However, to achieve this scale will require not only the trapping improvements described above, but also a strategy for making the display robust to environmental disturbances.

5. ROBUSTNESS

OTD displays based on photophoretic trapping are susceptible to external environmental factors such as air movement and destructive user interaction (e.g., the user passes their hand through the image, knocking out the particle). In order for an OTD display to perform reliably outside a laboratory setting, improvements will be needed to counteract external factors. Improving trapping as described earlier in this paper would go a long way to mitigate the effects of air flow but would do nothing to prevent users from dislodging particles. To address this second case, it might be possible to replace the lost particle(s) quickly enough that the user would be unaware that a disruption had occurred. In the laboratory, using the automated pickup method described earlier, the authors were able to achieve a pickup success rate of over 87% [1]. If the particle reservoir were to be placed directly beneath image volume it might be possible to pick up new particles as quickly as *once a frame*. Having the capacity to replace the particle at the frame rate would effectively render the display insensitive to user disruption so long as that disruption was temporary. There is also little danger of reservoir exhaustion as the volume of the total number of particles lost would amount to less than one cubic centimeter even after a year of continuous use. For those concerned about air pollution, it should be noted that this worst-case cubic centimeter of cellulose dust would constitute only one small fraction of the tens of kilograms of dust—some of which is cellulose-based—that is generated in the average in American household every year [23]. It should be further noted, that the display, which is equipped with a dust-trapping laser beam, could actually be configured to act as an air sponge, scanning for dust and trapping it to leave the immediate environment cleaner than it found it.

6. SAFETY

The use of class 3B lasers in the current OTD display introduces some safety concerns that should be addressed before the display is developed outside the lab. A particle primitive in an OTD display can be viewed from virtually any direction. From most angles only scattered light from the particle can enter the viewer's eyes. This scattered light is strongly diverging and is unlikely to be dangerous, just as light bouncing off any other round, diffuse surface in the room would be tend not to be dangerous—and more so for OTD particles given their very small reflective cross section. The scattered optical power is estimated of the order of nanowatts allowing for comfortable viewing in average indoor lighting conditions. Brightness varies with illumination power as well as particle characteristics such as size and scattering pattern. However, if the viewer is staring along the line that connects the OTD image and the OTD projection aperture, they run the risk of having unscattered light enter the eye. This creates a practical limitation on view angle in the current display prototype without the use of protective equipment. The view angle of the display is not affected by this limitation, but safety measures must be taken in order to access this portion of the view. This unscattered light is still diverging but could still be at a power density above maximum permissible exposure (MPE)—especially for the trap light, which cannot be dialed down as readily as illumination light while still preserving display function. It is possible that by improving the display as described above will obviate any additional solution as the traps become more efficient and more diffuse in multi-particle systems. However, it is worth exploring options for increased safety in the near term. The easiest way to make an OTD display safe at present would be to simply restrict the viewer to the large subset of view angles free of unscattered light. A second solution would be to have a second, angularly offset projector that could take over if the viewer should stray into the unscattered light. Another, preferable, solution would be to replace the violet trap light with infrared light which, depending on the wavelength, can have an MPE approximately 2 orders of magnitude larger than the MPE of visible light [24]. Ultimately, it is likely that a combination of these solutions will be employed to make the scaled display as safe as possible allowing for unfettered viewing and paving the way for advanced improvements like occlusion, that would make particularly good use of the OTD's potentially unlimited view zone.

7. OCCLUSION

Occlusion was long thought to be impossible for volumetric displays, but this has been shown not to be a fundamental limitation [25,26] so long as volumetric display point primitives can be made to scatter *anisotropically*. Anisotropic scatter is more difficult for some point primitives than for others. Plasmas, for example, scatter in a roughly isotropic manner. However, optically trapped particles can also scatter light in an isotropic manner [Fig. 3(c)] or an anisotropic manner[Fig. 3(d)] [27]. Figure 3(a) shows a cross section of a setup, in which a trapped particle is surrounded by several mirrors, making it possible to view and photograph a particle from multiple angles simultaneously [27]. It should be noted that the beam shown in Fig. 3(b) consists of 405 nm light and 532 nm light for trapping and illumination, respectively. These two superimposed beams remain in a fixed orientation through all trials. In Fig. 3(e) we see simultaneous photographs showing an isotropic particle scattering with similar intensity across multiple angles. Figure 3(f) we see particle scattering anisotropically—strongly in the 104 direction but weakly in the 26 direction. In order to achieve occlusion in OTD images, it must be possible for each particle to have control over its direction of scatter, so that one set of particles can

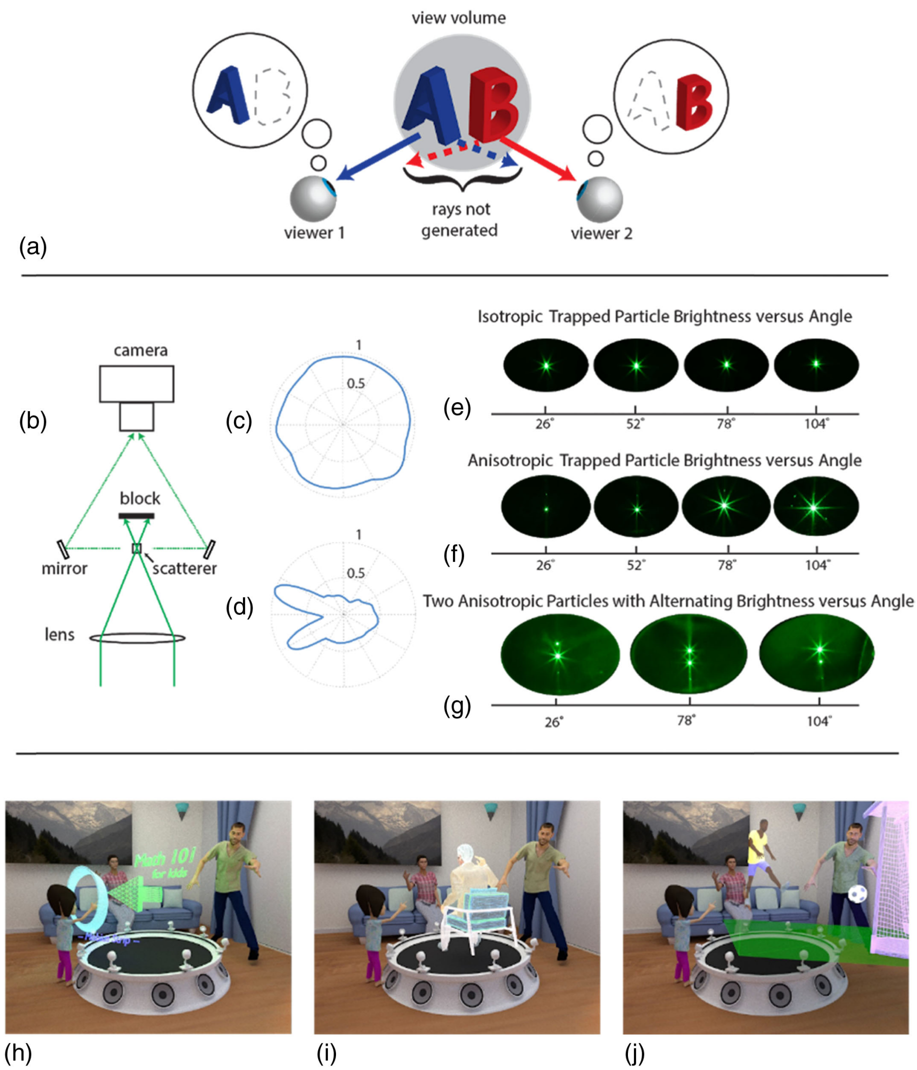


Fig. 3. Occlusion. (a) Anisotropy makes it possible to eclipse or occlude objects. (b) Setup for observing scatter from multiple angles simultaneously. (c) Isotropic scatter. (d) Anisotropic scatter. (e) Particle exhibiting isotropic scatter; this particle has relatively uniform scatter over 4pi steradians. (f) Particle exhibiting anisotropic scatter. (g) Two particles, one above the other, demonstrating alternating brightness moving from front to back [27].

wane in intensity while another, occluding, set waxes in intensity. The alternation of brightness is demonstrated in its most primitive form in Fig. 3(g) where two particles, one trapped above the other, alternate in brightness as the viewer position changes. This demonstration helps to establish the possibility but not necessarily the *feasibility* of occlusion in OTD systems. To achieve controlled, directional scatter in OTD systems would require a considerable feat of engineering. Visualization 1 shows observed particle behavior which supports the feasibility of predictable particle dynamics and observed behavior of rapid irregular motion. Previous work explores particle jitter and the relationship between simultaneously trapped particles [28]. The results in Visualization 1 were gathered experimentally using charcoal particles caught near the focus of a 4.5 W, 532 nm laser beam (Coherent Verdi) directed from left to right. The upper right video (labeled Rotating Particle) shows a particle caught in 50 torr of air. The other three videos were captured at 760 torr of air. The movies were taken using a Pulnix TM7 CCD camera at 30 frames per second through a 20× microscope objective. The experiment labeled "Rapid Tumbling" shows what is believed to be a common particle behavior by the authors and suggests some of the technical challenges that will need to be addressed in order to create an OTD capable of asserting control over particle behavior. The change in ambient pressure of the experiment has been shown [29] to affect particle trapping power requirements. All experiments were performed at approximately 760 torr except the "rotating particle" experiment. It was our assumption that the movement of particles in the trap would be rapid and irregular (other researchers have suggested as much [30,31]). This video shows motion that is ponderous, regular, and nearly periodic. A rotating anisotropic particle could be used to strobe through view angles like a lighthouse to provide angular control and occlusion effects. These videos show observed behavior critical to the proposed idea of a multi-particle OTD. The observation of both fixed relative orientation and relative spatial position allows for particle arrays to be assembled that are sufficiently stable to maintain their independent positions required to be used as independent voxels in a multi-particle OTD. Furthermore, the fixed particle orientation experiment suggest that complex particle geometries could be employed as a method of creating controlled anisotropic point primitives within a multi-particle OTD. Specifically, the particle on the left in the experiment "Fixed Relative Particle Orientation" shows a profile shape of a two-sided corner reflector geometry that can be highly directional in scatter.

To illustrate the possibilities and the challenges, the authors would suggest two potential strategies for creating occlusion in OTDs. The first is the "intelligent particle" method. In this method one begins with a particle that is big enough to reflect directionally, faceted might be preferred. Then the particle is made to tumble with a known period within the trap. Slowly rotating trapped particles have been observed (see examples of common particle dynamics in Visualization 1). Once the rotational period and phase are determined (this could be done by probing the particle in advance of the illumination with an invisible IR beam) the particle could be illuminated in synchrony with its rotation to provide controlled directional scatter. Within the "intelligent particle" approach there may also be room for luminescent or active particles [32,33]. The second method, the "intelligent illumination" method, was suggested as an alternative [34]. In this method, the spherical particle is illuminated only partially. The illumination light is carefully focused onto the region on the spherical particle's surface that will result in light scattering in a desired direction. Both of these approaches require a great degree of control of the illumination and/or the particle dynamics. The experiment shown in Fig. 3(b) does not demonstrate control over anisotropic scattering but instead suggests that irregular particle morphologies can be trapped and illuminated producing anisotropic scattering, as shown in Figs. 3(e)–3(g). The development of such a system would certainly be nontrivial, and the bandwidth required for such a display would scale linearly with the number of viewers; however, if developed successfully, the creation of a free-space display capable of occlusion would overcome one of the most persistent, most ubiquitous, and most vexing limitations of volumetric displays.

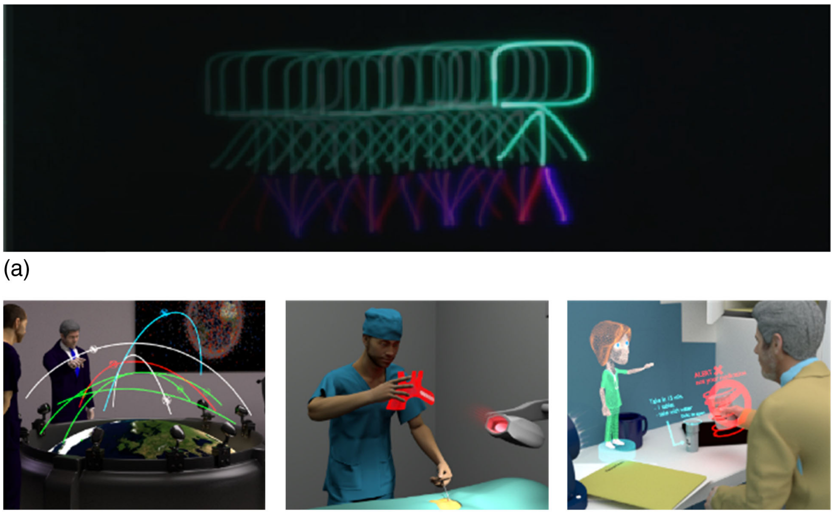
The advantages of an occlusion-capable OTD display would extend far beyond the ability to make images that self-eclipse and look self-solid. In fact, the ability to control directional scatter in such a display is no less than the power to control what every viewer sees—even when they are all looking at the exact same spot in the view volume. This prospect has remarkable ramifications for the utility of the display. Each viewer can be gazing at the same volume of space but seeing something customized to their proclivities, or security clearance, or native language. Imagine a future in which such a display exists in a family living room, as depicted in Figs. 3(h)–3(j). In the first panel, the family's daughter traces her finger along the surface of a mobius strip as part of her "Discovering Math 101" class. In the second panel, the mother, who is gazing into the same volume, is seeing and talking to a volumetric image of grandpa. In the final volume, dad is living his dream of winning the world cup as part of an immersive volumetric sports program. When coupled with highly directional parametric speakers, each of these participants could be having entirely independent or carefully interwoven immersive 3D experiences, yet none of them are wearing goggles, or staring at a screen. Their eyes are visible to us and to each other (how different from the family rooms of today!).

8. APPLICATIONS

The number of possible applications of OTD displays grows rapidly with the display's size, and it is worth a pause to consider what applications might be most appropriate for a next-generation display with a linear dimension of 20 cm (or approximately 8 in). The authors suggest that early target applications might include aerospace surveillance, image-guided catheterization, and corporeal AI agents. All of these are applications which leverage the OTD's unique advantages.

A. Surveillance

In light of recent announcements of major corporations to create large satellite constellations [35], the need for surveillance to avoid satellite conjunctions is greater than ever [36]. Currently practitioners abstract information from a 2D screen.



(a)

(b) (c) (d)

Fig. 4. Interactive applications. (a) Composite of photos from first OTD animation (see Visualization 2). (b) Satellite surveillance concept. (c) Guided catheterization concept. (d) Corporeal AI agent "holonurse" concept.

A free-space volumetric display could make the spatial relations of these objects viscerally apparent even as they move in relatively complex nonlinear trajectories. In air traffic control this technology could mitigate the cognitive loading and increase decision confidence in one of the more stressful jobs still performed by humans [37].

B. Medicine

During catheterization, medical practitioners must navigate tortuous 3D paths that get progressively more complicated as they approach the human heart. A volumetric display update with x-ray data could help practitioners understand the 3D path they are navigating and perhaps avoid arterial abrasion and the possibility of abrasion, embolism, and later deep vein thrombosis [38] [Fig. 4(c)].

Both of these applications are similar in that they value precise spatial relationships above other considerations such as photorealism. The datasets are also sparse by 3D standards [20]. These criteria help to make these attractive first applications for scaled volumetric displays.

C. Corporeal AI Agents

In Fig. 4(a), and in Visualization 2, the authors demonstrate a simple, animated OTD image—a color stick figure walking, and leaping, both in space and on the researcher's finger. This early-stage test for interactive images suggests the possibility of corporeal agents that exist within an individual's interactive space—within arm's reach. The researchers imagine a scenario like a holonurse shown in Fig. 4(d) in which a corporeal AI agent is tasked with helping an aging loved one. This "holonurse" could help with medication compliance, serve as a portal to emergency healthcare services, and point out fall dangers. This agent could be projected from a fixed OTD, a projector on a rail, or from a portable device so that it could remain with the senior as they went about their daily tasks. The agent would interact naturally within the senior's space and never once require them to look at a screen. Real-time animation was achieved on an OTD through continued development of software focused on drawing speed and added additional features required for proper display of animation. This included mechanisms for tracking the position within frames while drawing to allow for frames to be seamlessly stitched together, lateral movement offsets to allow the animation to walk across the display while reusing the positional data of earlier frames, and frame repetition to allow for longer animation sequences to be displayed compared to limitations in memory. One of the main challenges we faced in animation was memory storage limitations of the Arduino Mega that our original prototype was built on. The Arduino Mega has 256 kB of memory which we stored the functional code of the display and the animation data. In order to optimize for speed, we removed all real-time interpolation computations as these slowed down the response time of the display. Removing these interpolation steps allowed for higher frame rates giving stronger persistence of vision; however, it came at the cost of memory as we now precomputed interpolation and saved all the values into the memory of the Arduino Mega. This created a trade-off between speed and available data. The data was also limited by the complexity of the individual frames; more complex geometries required more positional data per frame.

9. CONCLUSION

These applications point to a screenless future in which our data becomes a physical part of the world around us. In so doing they could give us godlike creative powers—to literally bring forth new creations from the dust, breathe AI life into them, and send them forth to live with us. By exploring the improvements that should be part of the next generation of OTD displays the authors hope to focus the efforts of interested researchers and establish a vision for a new screenless paradigm for interacting with data.

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