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Holographic and Volumetric Mid-Air Display Technologies

Mid-air **3D holographic displays** – reminiscent of sci-fi “Princess Leia” projections – are becoming feasible through advances in computer-generated holography (CGH) and volumetric display technologies. This report surveys the state-of-the-art in *free-space* 3D displays, focusing on mid-air interactive/public demonstrations (often described with metaphors like a “magic missile” spell visualized in air). We emphasize **volumetric displays** that create tangible 3D visuals in open space (fog screens, scanned volumetric voxels, etc.) over near-eye waveguide or standard light-field panels, except where relevant. Key technical considerations include CGH algorithms (especially phase-only SLM methods), common artifacts and resolution limits, and safety constraints for public demos. We include foundational developments from the 1990s/2000s and major advances in the past decade.

Computer-Generated Holography (CGH) and Phase-Only SLM Algorithms

Computer-generated holography uses spatial light modulators (SLMs) to actively generate holograms – interference patterns that diffract illumination to form 3D images. In an ideal holographic display, *all* depth cues of a scene (continuous parallax, focus/accommodation, etc.) are reproduced by encoding the full optical wavefront [1] [2]. Modern CGH systems typically employ **phase-only SLMs** (e.g. liquid-crystal or MEMS devices) that modulate the phase of light, since dynamic amplitude+phase modulators are impractical. This imposes a need for specialized **phase-only hologram algorithms** to encode a desired 3D image into a phase-only pattern. Numerous methods have been developed, broadly falling into *two* categories: **wavefront-based** and **ray-based** algorithms [3] [4].

- *Wavefront-based CGH:* These physically simulate wave optics – for example, by propagating light from a 3D model (point cloud or polygons) and computing the interference pattern with a reference wave [5]. Essentially, the hologram is calculated by summing or integrating contributions of each object point’s spherical wavefront arriving at the SLM. Wavefront-based algorithms (e.g. Fresnel transform, point cloud diffraction summation) are accurate to optical physics and can encode true depth focus, but they are computationally intensive. Even with modern optimizations, generating a high-resolution hologram this way can be slow, and rendering photorealistic detail (textures, fine shading) remains challenging [6] [7]. On the upside, these methods naturally produce **full-parallax** holograms (both horizontal and vertical perspective changes). Classic examples include Fourier hologram computation and point-based coherent summation; more recent work integrates polygon rendering and even deep learning to accelerate wave propagation calculations [8] [9].

- *Ray-based CGH:* These methods treat the target 3D image in terms of *view-dependent 2D projections* (a light field), rather than directly computing wavefronts [3] [4]. For instance, a **holographic stereogram** approach takes multiple 2D images of the scene from different angles and encodes them into a hologram using interference patterns that recreate those views for the corresponding directions. In other words, the hologram is synthesized from incoherent ray bundles or multiview images instead of a full physical simulation [10]. Ray-based techniques (including holographic stereograms and layer-based or multi-planar methods) sacrifice some physical accuracy – they do not rigorously compute diffraction between object points – but they *gain* in speed and can reproduce realistic texture and shading from the input images [11]. They essentially reproduce a **light-field** similar to other multiview 3D displays, so certain wave phenomena (like focal blur outside a specific depth) may not be perfectly rendered. Nonetheless, they are much faster and have produced some of the most photorealistic holographic images to date [11]. The trade-off is that ignoring parts of the wave physics can introduce depth inaccuracies or focus issues for very close or far objects [12]. In practice, many real-time holographic video systems use hybrid approaches – e.g. computing holograms from layered depth images or point sprites (a mix of ray and wave concepts) to balance quality and speed [10].

Phase-only algorithm examples: Early algorithms for phase CGHs include the *Gerchberg-Saxton (GS)* iterative phase retrieval (1970s) which seeks a phase pattern that produces a desired intensity image (often in the hologram's far field) [13]. GS and its variants iteratively enforce constraints between the SLM plane and the image plane, refining the phase – these can achieve good results but are relatively slow. Faster, one-step methods exist as well: e.g. computing a *Fourier transform* of the target image and then taking only the phase ("kinoform" holograms [14]), or adding a random phase to the target and doing a single propagation calculation. One-step methods are extremely fast but often introduce artifacts like **ringing** (oscillatory ripples) or a granular **speckle** texture due to lost amplitude information [15]. Recent research has produced advanced techniques such as *double-phase encoding* (encoding a complex amplitude by two phase layers or a phase dither) to effectively modulate amplitude with a phase-only SLM [13] [16]. This **complex amplitude modulation (CAM)** can improve image fidelity (no twin image, less noise) at the cost of efficiency: effectively it uses two phase "pixels" per one complex sample, halving the effective resolution [16]. There is also growing interest in applying **non-linear optimization and AI** – for example, *gradient descent* algorithms and deep learning models have been used to optimize phase holograms for higher image quality and speed, showing promise for real-time dynamic holography [17] [9].

Common CGH Artifacts: Despite progress, CGH outputs still suffer from several artifacts and limitations:

- **Speckle Noise:** Holographic images often have a grainy, shimmering noise known as speckle. This arises from the coherent interference of light – tiny phase errors or the random phase used in algorithms cause adjacent hologram fringes to create random intensity granules in the image [18] [19]. Speckle not only reduces image clarity but also can cause unpleasant shimmering for viewers. *Speckle suppression* is an active research topic [20]. Techniques include introducing **multiple independent hologram frames** and averaging their reconstructions (time-multiplexing) [21], so that speckle patterns average out (this requires high SLM refresh rates, and may blur moving content). Another approach is using **partially coherent illumination** instead of a fully coherent laser – e.g. an LED or a laser with a rotating diffuser – to reduce spatial coherence and thus speckle [22]. This can substantially smooth the image at the cost of some holographic sharpness. Specialized algorithms can also address speckle by randomizing phase in the CGH in controlled ways: e.g. adding a pseudo-random phase mask to the target image (known as **RAP – random phase – methods**) to diffuse interference between object points [23] [24]. Recent "RAP-free" algorithms try to avoid needing random phases at all, thereby inherently reducing speckle [25]. In practice, a combination of approaches (optical and algorithmic) is used in modern demos to make holograms more clear and speckle-free [24] [26].

- **Twin Image & Zero Order:** In classical on-axis holography, the reconstruction contains a "twin" image (a blurred or conjugate duplicate) and a strong DC zeroth-order spot, which overlap with the desired image. This is a result of having only intensity or only phase recorded. Foundational work in the 1960s solved this by using **off-axis reference beams** – essentially adding a carrier angle so that the twin image and DC are separated from the main image in space [27]. Modern CGH systems typically incorporate an off-axis tilt in the phase pattern or a carrier grating on the SLM to direct the unwanted orders away from the viewing window. Alternatively, using complex modulation (as mentioned above) or algorithms that enforce one-sided output can eliminate the twin image numerically. Ensuring the SLM is calibrated to have zero average phase (to minimize a central bright spot) is also important. In short, **off-axis holography** (a technique dating back to Leith & Upatnieks) or equivalent numerical tricks are standard to avoid twin image artifacts [28].

- **Limited Diffraction Angle / Narrow Viewing Zone:** Because an SLM has finite pixel size and spacing, the hologram behaves like a diffraction grating with a maximum angle. The **field of view** or viewing angle of a CGH is roughly $\theta \approx \lambda/d$ (where *d* is the pixel pitch). With typical SLM pitches (~8 μm) and visible light, θ is only a few degrees – meaning the holographic image can appear in a very narrow cone unless optical tricks are used. One trick is to use a large Fourier lens to convert the hologram into a real image at some distance, trading angle for size. Even so, creating wide-angle, large-area holographic images is extremely challenging with current pixel sizes. Researchers have demonstrated some improvements – e.g. using **tiling or piecing** multiple SLMs together to effectively enlarge the hologram, or **scanner systems** that time-multiplex different hologram sections to cover a larger field [29] [30]. An example increased the effective pixel count by optically scanning a small SLM across a larger aperture [29]. Another approach confines holographic reproduction to **horizontal-parallax-only (HPO)**, where vertical parallax is sacrificed to allow a wide horizontal viewing zone (useful for many viewers spread laterally) [30]. HPO holographic displays were pioneered to reduce computational and hardware requirements at the cost of some 3D realism. In summary, the diffraction-angle limit remains a fundamental resolution issue.

Resolution Limits and Space-Bandwidth Product (SBP)

Whether holographic or other light-field displays, a key figure of merit is the **space-bandwidth product (SBP)** – essentially the total number of independent sample points that can be displayed. For a holographic SLM, SBP is approximately the number of pixels, and it must be "spent" on both field of view and image resolution. For example, a state-of-the-art 1080p SLM (~2 million pixels) might produce either a decent-resolution small image or a larger image with very coarse detail, but not a large high-detail 3D scene. For truly realistic 3D, **huge SBP** is needed (by one estimate, tens of gigapixels of SBP for a modest-size, wide-angle 3D scene) [31]. This is why today's holographic displays often have limited size or require the viewer to look through a small aperture. *Limited SBP of existing SLMs is a major bottleneck* – current holographic displays "cannot meet the requirements of humans" for both resolution and field size simultaneously [32] [33].

Researchers are tackling this in several ways. Improving **SLM hardware** is crucial: advances in liquid-crystal over silicon (LCoS) panels have increased pixel counts and reduced pixel pitch somewhat, and novel devices like MEMS-based optical phased arrays promise much smaller pixel sizes (a few microns or less) [34] [35]. There is also exploration of **meta-material SLMs** (nano-fabricated surfaces that modulate light at sub-wavelength scales) which could dramatically boost resolution if made dynamic [36] [32]. On the algorithm side, techniques that **trade off quality for speed or vice versa** are being combined: for instance, *optimized regional holograms* or *layered hologram decomposition* can handle larger scenes by dividing the content and computing sub-holograms [8] [17]. Also, *compressive and tiled holography* have been tested – where only parts of the hologram active at a given time refresh, or multiple smaller SLMs each project a portion of the scene. Despite these efforts, a breakthrough in SBP (perhaps using large arrays of modulators or future photonic chips) is needed for truly high-density, room-sized holographic projections. As noted in a 2022 review, **holographic display will need higher resolution, smaller pixel pitch, and better modulators to achieve its full promise**, though rapid progress suggests eventual solutions [33] [37].

It's worth noting that *near-eye* holographic displays (for AR/VR headsets) face similar SBP challenges, but since they only need to cater to one eye at a time in a small eyebox, they can use different tricks (scanning, pupil-tracking, etc.) [38] [39]. For this report, however, we focus on **free-space displays** that create images in mid-air viewable by unaided eyes in a public setting.

Volumetric and Free-Space 3D Display Technologies

Outside of true holography, many **volumetric display** techniques have been developed to produce 3D visuals in mid-air. A volumetric display generates imagery by **emitting light from points in a 3D volume**, rather than just a 2D screen projection [40]. This typically means the 3D image can be viewed from any angle (360°) and does not require special glasses. However, conventional volumetric systems usually have a *fixed volume or device* that contains the points, and touching or intersecting that volume can disturb the image or pose other challenges [40]. Here we summarize major types of volumetric/free-space displays, emphasizing those suitable for interactive or public demos:

- **Swept-Surface Volumetric Displays:** These use a moving 2D surface that rapidly sweeps through a volume, displaying a series of slices that the human eye integrates into a 3D image. A classic example is a rotating LED array or a fast oscillating screen inside a transparent enclosure. One commercial product is the Voxon **VX1** display – it has a flat panel that oscillates up and down while a projector shines 2D images on it at ~3 kHz; the result is a 3D volume ~18×18×8 cm that multiple people can view simultaneously [41]. Such displays produce genuinely volumetric images (volumetric voxels), so viewers can see different sides of an object by moving around it. They also naturally support **motion parallax** and correct focus at the voxel locations (since light is actually emitted at those 3D points). However, resolution is usually much coarser than flat displays. In the VX1, for instance, the effective voxel count is limited by the projector resolution and number of slices – the images look noticeably "pixelated" or sparse compared to even a standard 2D screen [31]. Table-top volumetric displays often have on the order of 10^8 voxels per second capabilities, which translates to a few hundred voxels in each dimension at video rates [42] [43]. Another limitation is **lack of occlusion**: since volumetric voxels emit light in all directions, a "foreground" object won't block a "background" object – everything is semi-transparent. All points are visible through each other, which can make the imagery look ghostlike and unrealistic. As one researcher famously stated, *"you don't have the self-occlusion to make objects look realistic"* in most volumetric displays [44]. Recent research is exploring ways to introduce occlusion, such as using multiple *anisotropic* voxels or directional emission that depends on viewing angle [45] [46], but in general, traditional volumetric displays depict semi-transparent 3D forms. Despite these issues, swept-volume displays have been used in compelling demos and are among the only techniques that provide 360° multi-viewer 3D with high brightness. Mechanical complexity and safety are non-trivial, though – see the *Safety* section for how spinning/oscillating parts are handled.

- **“Hologram Fans” (Spinning LED Fans):** A popular variation of the swept display is the so-called *holographic fan* – essentially a set of LED strips on rotating fan blades. When spun at thousands of RPM, the persistence of vision creates the illusion of a floating 2D image (or simple 3D if multiple depth layers are encoded) [47] [48]. These have become eye-catching advertising displays. They are not volumetric in emitting true depth, but often marketed as 3D holograms because the image appears in mid-air. They share similar advantages (bright, no glasses) and drawbacks: limited true depth, and the spinning blade mechanism can be dangerous if exposed [49] [50]. Typically, *protective enclosures or clear covers* are required in public settings to prevent people from touching the fast-moving blades [51] [52]. Some models integrate an outer acrylic drum or cage. As an added benefit, these enclosures can improve image quality by providing a dark backdrop and keeping dust off the device [53]. In summary, “hologram fans” are a cheap, simple form of mid-air display suitable for signage, but must be deployed with care to avoid mechanical hazards.

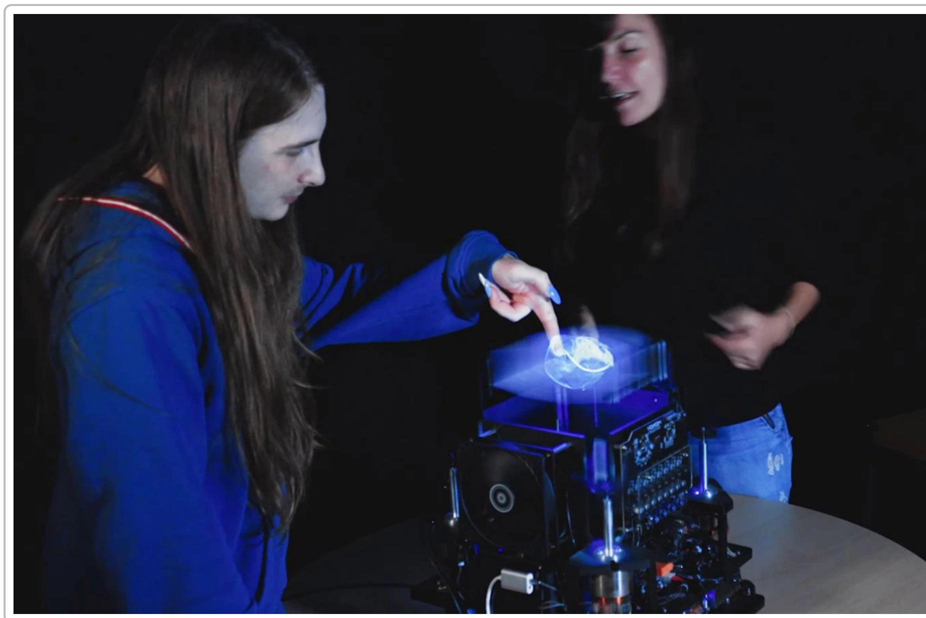
- **Static Volume Displays (Multi-layer or Stationary Voxels):** A less common approach is to fill a volume with some emissive points without moving parts. Early examples included stacks of transparent LCD screens or LED matrices layered to form a crude 3D image. Another intriguing method uses **photo-activatable materials** – for instance, a solid block doped with a phosphor that lights up at the intersection of two scanning laser beams (known as a 3D raster display). These can create a volumetric image inside a solid medium. A recent demonstration used a special photochromic dye that can be activated at voxel positions, but one challenge is erasing or updating the voxels, leading to “ghost” afterimages when beams intersect unintentionally [54]. Generally, static-volume displays struggle with refresh rate and often are limited to proof-of-concept or artistic installations. They are less relevant for interactive public demos due to limited dynamic content (though they do achieve true occlusion since the medium can block light behind illuminated points).

- **Mid-Air Particle Displays (Optical Trap or Acoustic Levitation):** A cutting-edge category uses actual *moving particles in air* as animation points. In an **optical trap display**, a tiny particle (like a dust speck or nanofiber) is trapped by optical forces (e.g. a focused laser beam) and rapidly moved in 3D space to trace out images. By illuminating the particle with visible light (RGB lasers or LEDs) as it moves, it can form a persistent 3D image *point by point*. In 2018, researchers at BYU demonstrated such a system – a single particle was steered at high speed to draw shapes like a butterfly and even simple animations in a volume of a few cubic centimeters [55]. The image is truly free-space and can be seen from any angle. This approach effectively is a **“3D printer” for light** in mid-air, in that the particle is writing the image in real time. The attainable complexity is currently limited by particle speed (and trapping force): typically, it can draw wireframe-style objects or low-detail volumetric forms. However, multiple particles could be trapped to scale this up, as some research suggests ways to control particle *arrays* for more voxels [56] [57]. Optical trap displays have a major advantage of **solid occlusion** – the particle can potentially block light behind it or be illuminated directionally, addressing the occlusion problem [45] [58]. Indeed, one vision is that each particle could act as a tiny steerable mirror or emissive point that only certain viewers see, enabling correct occlusion and even multi-viewer different images in the same space [46] [58]. This is still speculative and extremely complex to achieve. Current systems mostly use one particle. **Safety-wise**, optical traps often involve powerful lasers (to trap the particle) focused in a small area – typically the setups are enclosed or the laser is kept away from viewers. The particle is usually very small and poses no impact risk. Another similar approach uses **acoustic levitation**: ultrasound transducer arrays can levitate small beads or droplets and move them rapidly. While safer (no laser needed) and able to handle multiple particles, acoustic systems struggle to achieve fast motion and the particles are larger (millimeter scale), so the resolution is quite low. On the other hand, ultrasonic displays can *simultaneously* provide mid-air haptic feedback by using acoustic radiation pressure, letting users feel the floating objects. This has been demonstrated in simple forms (e.g. feeling a levitated bead or a virtual shape created by acoustic focal points). Overall, particle-based volumetric displays are a nascent but exciting area that promise tangible, interactive mid-air content, as long as their mechanical and optical constraints are managed.

- **Laser Plasma Voxels (Air Plasma Displays):** Perhaps the most futuristic-looking method is creating *points of light in thin air* by ionizing air molecules with intense laser pulses. This produces a tiny plasma flash – literally a **floating dot of glowing plasma** – at the focal point of a laser beam. By scanning the focal point in 3D, a sequence of glowing dots forms a 3D image that requires no screen or particle at all. A Japanese company, Aerial Burton, demonstrated an early version in 2014 that displayed floating 3D text and simple graphics by using a pulsed IR laser and a galvanometer scanner [59] [60]. The downside of using nanosecond pulses was that each plasma dot carried significant energy; touching the image could burn skin or at least felt painfully hot [61]. This obviously raised safety concerns: "you don't want to go walking through one of these displays, because it will burn you" [61]. To address this, in 2015 the same researchers (Ochiai et al.) developed a **femtosecond laser** based system dubbed *"Fairy Lights in Femtoseconds"*. By using ultrashort pulses (~ 10–100 fs duration) at high repetition, they create plasma voxels that emit light but with much lower thermal energy transfer [62] [63]. The plasma sparks are so brief that they do not burn upon contact – in fact, the team reported that the plasma is **"touchable"**: a finger placed at the focal point causes a brighter flash, and users feel a slight tactile pop like haptic feedback [64] [65]. The key safety principle is that extremely short pulses deposit less energy per pulse and avoid continuous exposure. Tests showed that if pulses lasted more than a couple seconds in one spot, they could burn a material, but pulses in the 50 ms to 1 s range caused **no damage to a leather sample** (used as a skin proxy) [66]. The femtosecond system thus allows safe interaction with the floating image – one can pass a hand through it with only a tingling feeling. These plasma displays remain limited in resolution and size – often just a few thousand dots per second, creating a small wireframe object maybe in a few-cm cube. Recent work is exploring using *spatial light modulators in the laser path* to form multiple foci or patterned clusters of plasma dots simultaneously [63], and even achieving **multi-color** by using different wavelengths or multi-photon processes [67]. Laser-plasma displays are highly appealing for outdoor and large-scale applications (since they don't need any medium except air), such as emergency signage floating over a road [68] [69], but for public use the laser system must be engineered with strict safety interlocks. Typically these use infrared or near-infrared lasers; although the plasma dot emits visible light safely, the IR beam itself can be dangerous if it escapes the intended focal region. In a controlled setting, however, this technology provides one of the most *magical* mid-air display effects – literal points of light forming a 3D image that one can touch.

- **Fog Screens and Aerial Projection Surfaces:** A different approach to "volumetric" is to use **immaterial screens** – thin films of translucent media like fog, mist, or even optical waveguides in air – to project images *into* the air. The image is still essentially 2D, but it floats on an invisible plane, and multiple such planes or other optical tricks can create a 3D illusion. The most well-known is the **FogScreen**™ – a device that produces a laminar sheet of dry fog (water vapour with glycol) that serves as a rear-projection screen for a video projector [70]. The result is a high-contrast image that literally hovers in mid-air; viewers can walk around it or *through* it, as the fog curtain is thin and disperses as you pass (earning the description of a "walk-through screen") [70] [71]. This technology became popular in museum exhibits and theme parks for creating ghostly apparition effects.

Technically, it's not a true 3D display (it's a flat image plane), but it's often integrated into AR installations or combined in layers for depth. FogScreen's innovation was making the fog sheet stable – an unprotected fog will quickly become turbulent and blur any image [71] [72]. The device creates a smooth laminar airflow that sandwiches the fog, keeping the screen region about 1 cm thick and relatively stable for 1–2 m of drop [73]. Image quality on fog is surprisingly good: resolution can be high when viewed near-perpendicular. At oblique angles the image blurs (because the screen has depth – ~1 cm – so pixels overlap from that viewpoint) [73] [74]. Also, the lower portions of the fog sheet eventually destabilize (it's a "living surface"), causing some distortion in the image towards the bottom [75]. Nonetheless, for most entertainment and signage uses, the fog screen produces adequately sharp and bright mid-air images, with the huge advantage of being **fully penetrable** – you can reach into an image or walk through it without harm (just a slight feeling of cool mist). Interactive systems have used infrared touch tracking on fog screens to create mid-air **"touch displays"**, where users manipulate floating content with their hands. Beyond FogScreen, other mid-air screen techniques include *water mist displays* (e.g. spraying a water haze to project on), and *aerial glass* (using a transparent mirror to project an image that appears to float in front of a background). A notable optical method is **Aerial Imaging by Retro-reflection (AIRR)**, where a projector and retroreflective material can form a real image in mid-air that multiple people can see. This is achieved by an optical combiner that folds the image's light back into space; it's not volumetric (the image is typically a 2D plane floating at a fixed distance). Such systems have been used for interactive kiosk displays where the content appears between the user and a background screen, enabling mid-air gesture control. Overall, these mid-air projection techniques are somewhat simpler and safer since they rely on diffuse light and passive media – there are **no lasers or moving parts** in direct contact with the user, only light and perhaps some water vapor. The trade-off is that they do not provide multiple depth layers by themselves (except via stereoscopic illusions), and environmental factors (ambient light, air currents) can impact performance.



Example of a user interacting with a mid-air volumetric display. Here the **FlexiVol** system uses an elastic oscillating diffuser to display a 3D image that can be safely "touched" [76] [77]. Traditional swept-surface volumetric displays used rigid fast-moving screens, so any contact could **"cost you a finger" or break the machine** [76]. FlexiVol's stretchable screen yields to touch without damage, allowing direct hand interaction with the floating image. This design demonstrates how innovations in materials can address safety and interactivity limits in volumetric 3D displays.

Safety Constraints for Public 3D Displays

When taking these holographic or volumetric displays out of the lab and into public installations, **safety is paramount**. There are two main concern areas: **eye/skin safety** (optical radiation and bright light exposure) and **physical/mechanical safety** (moving parts or structural hazards). Any public-facing demo must comply with laser safety regulations, avoid causing discomfort (e.g. seizures from flicker or glare), and prevent accidental injury. Below we outline the key safety considerations and solutions:

- **Laser and Light Safety:** Many mid-air display techniques involve high-powered light sources (lasers for holograms, projectors, etc.). Lasers, in particular, can pose serious eye hazards if the beam or its specular reflection hits an observer's eye. Even a <1 mW laser pointer can cause eye damage if directly stared into [78]. Public holographic displays typically ensure that no *static* laser beam is exposed to viewers – the light is either diffused (spread out as an image) or scanned so rapidly that the time-averaged exposure on any given eye spot is below the safe limit (the **MPE: Maximum Permissible Exposure**). For example, lasers used in scanning projectors or hologram systems are often Class 3B or 4 in raw power, but when projected as an image the energy per area is reduced. **Audience-scanning laser shows** have long established that fast-moving beams can be safe if properly power-calibrated [79] [80]. Modern laser projectors and holographic display units include safety features like beam shutters, scan-failure detectors (to cut off the laser if the beam stops moving), and sometimes **eye-tracking** to actively blank if a viewer is looking too directly. In holographic near-eye displays, the approach is different (since light is aimed into the eye) – they use expanded low-power beams equivalent to safe LED brightness, or pupil replication to avoid any high-intensity point. For **free-space holograms**, often the simplest path is using relatively low-power light sources. Many "holographic" displays actually use **LEDs** or other incoherent light for illumination (for example, some hologram-like effects on fog screens or fan displays). These are generally within normal display brightness standards and pose no greater risk than digital signage.

  With the more *exotic* systems like plasma or optical trap displays, safety considerations become specialized. **Laser plasma displays** must deal with powerful IR laser pulses: the "Fairy Lights" femtosecond display is designed so that the laser focus is only at the intended image points and each pulse is ultrashort, minimizing heat transfer [63] [81]. The system demonstrated that keeping pulse bursts under ~50 ms avoids burning skin [66]. Moreover, the plasma itself emits visible light safely; it's the IR beam that could be hazardous if it continued beyond the focal point. In practice, these setups would be enclosed from the side or use beam dumps beyond the working volume to capture any stray beam. Users are *not* meant to look directly into the laser path (which is invisible IR); they only see the glowing points. By using **femtosecond pulses**, the researchers achieved a level where touching the hologram is safe – no skin damage and a tolerable sensation [65] [81]. Nevertheless, such a device in public would likely be operated by trained personnel, with barriers to keep viewers from putting their eyes close to the emission point. **Optical trap displays** similarly use lasers (often a focused 532 nm beam for trapping). These are typically Class IV lasers (~watts of power) converging in a small region. In a lab setting, they are enclosed or on an optical table to prevent accidental exposure. For a public demo, one would need to enclose the trapping region in glass or ensure the beam can't escape if the particle is absent. It's worth noting that the *illuminating* light for the particle (the RGB that makes it visible) can be low-power, since the particle is so small – a few milliwatts of RGB laser can suffice for the visible part, and those can be eye-safe if diffused. It's the trapping beam that's the hidden hazard.

In summary, **regulatory compliance** is needed for lasers in public. Many countries require demonstrations to be classified as **Class 1 or 2** laser products (completely eye-safe even for long exposure) unless special permits are obtained. Achieving Class 1 often means fully enclosing the beams or using interlocked scan systems so no harmful static beam can hit an observer [82] [79]. In entertainment, standards like IEC 60825 and FDA regulations in the US govern these. Designers will incorporate redundancy in safety – for instance, two independent methods to cut off the laser if scanning fails, or use of **physics** (e.g. a rapidly diverging beam that even at full power diffuses beyond the danger distance). **Visible brightness** is another factor: extremely bright holographic images could cause glare or afterimages. This is usually only an issue if using intense projection; e.g. a plasma voxel is as bright as a small firework spark – luckily they are tiny and brief. Still, for audience comfort, displays shouldn't produce sudden blinding flashes in dark environments. Hologram fans and LED-based systems should avoid PWM flicker in the 3–50 Hz range that could cause seizures in photosensitive individuals; most run at high refresh rates so this is not a problem. All told, with careful engineering, the optical risks of mid-air displays can be mitigated to acceptable levels, as evidenced by public laser shows and interactive demos that have operated without incident.

- **Mechanical and Interaction Safety:** Many volumetric displays involve moving parts – rotating mirrors, spinning screens, fast oscillating diffusers, etc. In a public scenario, one must prevent people from touching or obstructing these moving parts, both to protect the person (e.g. from cuts or pinches) and to protect the device (since an unexpected touch could break the mechanism). The story of **FlexiVol** (mentioned above) nicely illustrates the issue: earlier swept-volume displays used rigid spinning surfaces moving at thousands of RPM, so *any* attempt to reach into the image could end in injury or device damage [76]. Standard practice is to put such displays **in a protective enclosure** (transparent casing). For example, the Voxon VX1 normally comes with a clear dome covering the oscillating screen [41]. The dome ensures fingers cannot accidentally hit the plate, and if the cover is removed, the system is designed such that an accidental touch will not break anything nor seriously hurt the finger [41]. (The moving screen in Voxon is lightweight and will just stop if impeded, rather than slicing into the object.) Similarly, the popular rotating LED **hologram fan** displays *must* be encased when used within reach of the public. As a report on their use notes, without protection "the lack of protection may lead to physical injuries or property damage" in public spaces [50]. The recommended solution is a **transparent acrylic shield** around the fan blades [51], which physically blocks any contact and also catches any small debris if a blade were to fail/break. These housings are usually part of the certified product design for commercial use [83] [84].

Another aspect is structural safety – some volumetric installations, like large fog machines or multi-projector rigs, need to be secured so they won't topple if jostled by crowds. Any hanging components (like a ceiling-mounted fog screen) should have safety cables, etc. While straightforward, these considerations are important for public demos (for instance, an early large steam-based volumetric display built at MIT was only shown behind a thick glass shield *"in case of a steam explosion"*, highlighting the caution required [85] [86]).

Interactivity and ergonomics: For interactive mid-air displays, ensuring user safety also means making interaction intuitive and comfortable. If users will reach in to "touch" holograms, the system should avoid any sharp edges or pinch points on its physical enclosure at the reach-in area. Ultrasonic haptic feedback arrays, if used, should be within safe acoustic levels (prolonged exposure to very intense ultrasound can cause headaches or dizziness). Fortunately, the frequencies used (typically ~40 kHz) are inaudible, and the focal points are low energy, so this is usually fine. In optical haptic (laser plasma) feedback, it's important that the energy stays low – the femtosecond plasma method essentially leverages the fact that the plasma creates a tiny shockwave that is perceivable but harmless [65]. So far, the tactile feedback in such systems is light (like a static tickle). Ensuring that no one tries to stare closely at the focal point while seeking haptic sensation is prudent (perhaps a reason these are shown in supervised settings).

Another subtle point: mid-air images have no physical barrier, which is magical but also could surprise or disorient viewers. In public exhibits, sometimes **clear markers or lighting** are used to delineate the 3D viewing zone so people don't walk *through* an image unknowingly and, say, bump into other exhibit pieces. For AR exhibits blending real and virtual, good practice is to prevent situations where a user might try to lean on a "virtual" object and fall. While not a hazard of the display tech per se, it's a human factor to consider.

In conclusion, modern holographic and volumetric display technologies are advancing rapidly, enabling **truly three-dimensional, free-space visuals** that can be experienced by groups without wearables. CGH techniques offer the most faithful 3D reconstructions with all depth cues, but face challenges in computation and display resolution. Volumetric and light-field displays provide a different compromise – often lower fidelity or lacking occlusion, yet capable of 360° viewing and direct interaction. We now see hybrids and innovative solutions (like the femtosecond plasma for safe touchable holograms, and flexible screens for safe interaction) that address earlier limitations [62] [77]. Safety remains a vital constraint: any public 3D demo must rigorously limit optical power to eye-safe levels and shield users from moving elements and other hazards. Fortunately, decades of experience in laser shows, digital signage, and interactive exhibits provide a foundation of safety practices (from engineering controls to regulatory standards) that these new holographic displays can adopt [52] [84]. As display components continue to improve (higher SBP SLMs, faster modulators, brighter yet safer light sources) and algorithms grow more efficient [33] [36], the gap between today's prototype "holograms" and the vivid volumetric illusions of our imagination is closing. We can expect increasingly **comprehensive 3D experiences** – perhaps mid-air video games, educational demos, or art installations – that are both breathtaking and safe for public interaction. Each incremental advance, be it reducing speckle noise or extending viewing angles, contributes to making **science-fiction-like holographic displays** a practical reality [87] [3].

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