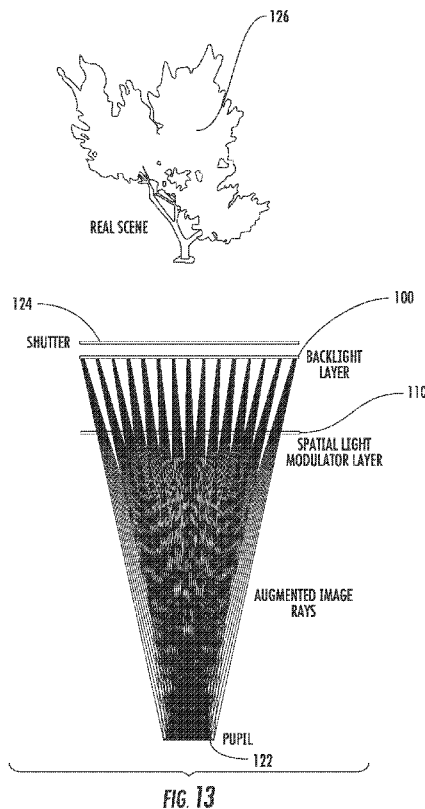




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(54) Title: OPTICAL SEE-THROUGH NEAR-EYE DISPLAY USING POINT LIGHT SOURCE BACKLIGHT



(57) Abstract: According to one aspect, the subject matter described herein includes a near-eye optical see-through display. The display includes a backlight layer including a plurality of point light sources. The display further includes a spatial light modulator (SLM) layer for modulating light from the point light sources. The spatial light modulator is located in the optical path between the point light sources and a user's eye. The spatial light modulator layer includes pixels that are controllable to modulate light from the point light sources such that the light that impacts the user's eye has a desired intensity and color to display a synthetic image. At least a portion of the backlight layer and the spatial light modulator layer are optically transparent to allow a user to view a real scene through the spatial light modulator layer and the backlight layer such that the synthetic image appears to be overlaid on a view of the real scene. Each pixel in the spatial light modulator layer modulates only a portion of the light emanating from the point light sources such that the synthetic image appears to be in focus to the user's eye.



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view that the user would normally see through corrective lenses in eyeglasses (about 100°). Conventional optical see-through displays provide less than a 100° field of view and many have complex optics, which increases the size and cost of the display unit. Accordingly, there exists a
5 need for a compact optical see-through near-eye display with an improved field of view.

SUMMARY

According to one aspect, the subject matter described herein includes
10 a near-eye optical see-through display. The display includes a backlight layer including a plurality of point light sources. The display further includes a spatial light modulator (SLM) layer for modulating light from the point light sources. The spatial light modulator is located in the optical path between the point light sources and the eye. The spatial light modulator layer
15 includes pixels that are controllable to modulate light from the point light sources such that light that impacts a user's eye has a desired intensity and color to display a synthetic image. At least a portion of the backlight layer and the spatial light modulator layer are optically transparent to allow a user to view a real scene through the spatial light modulator layer and the
20 backlight layer such that the synthetic image appears to be overlaid on a view of the real scene. Each pixel in the spatial light modulator layer modulates only a portion of the light emanating from the point light sources that enter the eye, such that the synthetic image appears to be in focus to the user's eye.

25 As used herein, the term "synthetic image" refers to any image that is desired to be superimposed on a user's view of a real scene. The synthetic image may be an image of a real object captured by a camera or a virtual image generated by a computer and that is not an image of a real object captured by a camera.

30 The subject matter described herein may be implemented in hardware, software, firmware, or any combination thereof. As such, the terms "function" "node" or "module" as used herein refer to hardware, which may also include software and/or firmware components, for implementing

the feature being described. In one exemplary implementation, the subject matter described herein may be implemented using a computer readable medium having stored thereon computer executable instructions that when executed by the processor of a computer control the computer to perform

5 steps. Exemplary computer readable media suitable for implementing the subject matter described herein include non-transitory computer-readable media, such as disk memory devices, chip memory devices, programmable logic devices, and application specific integrated circuits. In addition, a computer readable medium that implements the subject matter described

10 herein may be located on a single device or computing platform or may be distributed across multiple devices or computing platforms.

BRIEF DESCRIPTION OF THE DRAWINGS

The subject matter described herein will now be explained with

15 reference to the accompanying drawings of which:

Figure 1A is an image of a sparse array of point light sources, referred to herein as pinlights that fill the eye's image plane when held defocused near the eye;

Figure 1B is a perspective view of a prototype of an optical see-through near-eye display according to an embodiment of the subject matter described herein. The display includes pinlight arrays and spatial light modulators, which in the illustrated example are liquid crystal displays. The spatial light modulators code the defocused pinlights to form an image on the retina;

20

Figure 1C is a photograph taken through the prototype display illustrated in Figure 1B using a camera that approximates the human eye;

25

Figure 1D is an image illustrating a comparison of the field of view of the prototype display in Figure 1B (110°) to state of the art commercial optical see-through displays;

Figure 2 is a perspective view illustrating pinlight projection. A defocused point light source or pinlight, placed near the eye, is coded with a spatial light modulator to create a narrow field of view image that appears in focus without the use of refractive or diffractive optics;

30

Figure 3 is a view illustrating ideal tiled pinlight projector geometry. The display is configured that the pinlight projectors abut on the eye focused plane and on the modulation plane, creating a continuous image and using the SLM efficiently. (Note that the pinlights may emit light over a wide angle but only light entering the pupil is shown.);

Figure 4 is a perspective view illustrating tiled pinlights in a tracked virtual aperture configuration. An aperture mask is encoded over the desired image on the modulation plane to create a virtual hexagon aperture over the eye that can be tiled, eliminating toning effects in the perceived image. The image on the modulation plane is recomputed based on the tracked eye position to allow eye movement relative to the display. (Note that the pinlights may emit light over a wide angle, but only light that enters the pupil is shown.);

Figure 5 is a perspective view illustrating an untracked light field configuration. For each point on the eye focus plane, a set of rays is created through a tiled set of pinlight projectors that are distributed about an eyebox near the eye, allowing eye movement. The modulated pixels corresponding to the same point in the scene are distributed over the image;

Figures 6A-6F illustrate a waveguide based pinlight array. Figure 6A illustrates the array manufacturing process by creating small divots in an acrylic sheet using a needle attached to a robotic arm. Figure 6B illustrates that the waveguide contains a sparse array of divots. In Figure 6C, the divots are imperceptible and see-through when viewed with a camera with an aperture and focus similar to a human eye. Figure 6D illustrates that when illuminated from the side with an LED, bright light spots appear in the waveguide. Figure 6E illustrates that when defocused near the camera, the pinlights form discs that tile the image plane. Figure 6F is a line drawing of a lateral view of the waveguide illustrating how the surface imperfections in the waveguide create the pinlights;

Figure 7 is a top view of a portion of the prototype display illustrated in Figure 1B illustrating components of the display;

Figure 8 is a top view illustrating the prototype display and a protractor depicting camera mounting and display measurement. A camera

is mounted behind the display prototype that approximates a human viewer wearing eye glasses. A protractor is placed with the origin at the camera center of projection to measure field of view. An image taken through the camera is depicted in Figure 1B;

5 Figure 9 illustrates display simulations. The inset images of the word "field" illustrate magnified regions. The top left portion of Figure 9 illustrates a reference image, used as a target image for simulation. The top right image in Figure 9 illustrates the tracked configuration simulation. The bottom left image in Figure 9 illustrates the untracked configuration simulation (small eyebox). The bottom right image in Figure 9 illustrates the untracked configuration (larger eyebox);

 Figures 10A-10E are images illustrating an exemplary image formation process. The inset images in Figures 10A-10E show magnified regions. Figure 10A illustrates defocused pinlights forming overlapping discs on the image plane. Figure 10B illustrates a hexagonal aperture encoded in a modulation pattern. Figure 10C illustrates a displayed modulation pattern without the pinlights illuminated causing an out of focus image to appear. Figure 10D illustrates a displayed modulation pattern with the pinlights illuminated, causing an in focus image to appear. Figure 10E illustrates the virtual image displayed with a periodically displayed occlusion mask, improving see-through ability;

 Figures 11A-11F illustrate sample display inputs and results. The inset images show magnified regions. Figure 11A illustrates a modulation pattern for an augmented image sent to a display for a blue color channel. Figure 11B illustrates a photograph of a display while the blue color channel is displayed. Figure 11C illustrates a modulation pattern sent to the display as an occlusion mask. Figure 11D illustrates a photograph of the display while the occlusion mask is shown. Figure 11E illustrates a simulated reproduction of the augmented image. Figure 11F illustrates a photograph of an actual augmented image in background taken over a complete color and occlusion cycle;

 Figures 12A-12D illustrate sample results from the prototype illustrated in Figure 1B. Figure 12A illustrates a user interacting with a virtual

image of a teapot. Figure 12B illustrates a synthetic image of a tie fighter displayed over a real image of a poster on a wall in a room. Figure 12C illustrates text displayed to fill the entire field of view. Figure 12D illustrates a magnified image of a portion of the image in Figure 12C, which represents
5 a horizontal field of view of approximately 12°;

Figure 13 is a top view of an optical see-through near-eye display according to an embodiment of the subject matter described herein;

Figure 14 is a perspective view of another prototype of an optical see-through near-eye display according to an embodiment of the subject matter
10 described herein;

Figure 15 is a block diagram illustrating exemplary components of an optical see-through near-eye display according to an embodiment of the subject matter described herein; and

Figure 16 is a flow chart illustrating an exemplary process for
15 controlling an optical see-through near-eye display according to an embodiment of the subject matter described herein.

DETAILED DESCRIPTION

We present a novel design for an optical see-through augmented
20 reality display that offers a wide field of view and supports a compact form factor approaching ordinary eyeglasses. Instead of conventional optics, our design uses only two simple hardware components: an SLM and an array of point light sources (e.g. implemented as an edge-lit, etched acrylic sheet) placed directly in front of the eye, out of focus. We code the point light
25 sources through the SLM to form miniature see-through projectors. A virtual aperture encoded on the SLM allows the projectors to be tiled, creating an arbitrarily wide field of view. Software rearranges the target augmented image into tiled sub-images sent to the display, which appear as the correct image when observed out of the viewer's accommodation range. Spatial
30 resolution may be increased through the use of eye tracking. We demonstrate feasibility through software simulations and a real-time prototype display that offers a 110° diagonal field of view in the form factor of large glasses.

1 Introduction

Augmented reality (AR) offers a tantalizing vision for the future. Imagine leaving home to proceed along directions placed neatly on the sidewalk; along the way, a glance across the street yields the menu for a
5 cafe, prompting us to stop and share coffee with a remote friend apparently seated across the table. In this example, we imagine *casually* harnessing graphics with meaningful *spatial connections* to the world, at a moment's notice and at many moments throughout the day. We imagine computer
10 graphics transitioning from a distinctly external entity into a part of human vision.

Realizing this vision requires advances in many disciplines – low-latency rendering, tracking, application development, mobile computing, localization, networking – but perhaps the most fundamental problem is
15 obtaining a suitable display. A display that satisfies the long-term potential envisioned for AR must satisfy two key requirements:

Wide Field of View: Field of view (FOV) is a critical attribute of a *spatially registered* AR display. A synthetic object or information overlay registered to the world, however small, may over time appear anywhere in a
20 viewer's field of view as the viewer moves. Most envisioned AR applications also expect that a synthetic overlay could, at any given moment, fill an arbitrarily large portion of the viewer's FOV. Therefore, if the field of view of an AR display is less than the viewer's total field of view, registered objects and overlays will be cropped or will disappear and reappear with head
25 motion. This reduces the effectiveness of the display: the user now must take an active role to discover and keep synthetic overlays in view, may not receive complete information at any instant, and may have a reduced sense that overlays represent synthetic objects that are present in the world. Although the field of view of the human eye is nearly 180°, the field of view
30 achieved through the corrective lenses of ordinary eyeglasses – which generally span a $\geq 100^\circ$ horizontal FOV – suggests a pragmatic target.

Non-Encumbering: A display intended for *casual and extended use* must be ready to use in an instant, must be comfortable, and must not

interfere with other tasks when not being used. This requires a non-encumbering design: it must not be too bulky, and must not significantly degrade normal human sight. As with field of view, ordinary eyeglasses or sunglasses demonstrably achieve an acceptable level of encumbrance and provide a target standard. Although some bulk is generally accepted for research prototypes, it is important to consider the *minimum* size supported by a given design, which often has a hard lower limit due to optical constraints.

Recent developments in *optical see-through near-eye displays*, which superimpose synthetic imagery over a viewer's natural sight, tackle these two key requirements in isolation. Such devices have been demonstrated with a wide FOV (e.g. Cheng et al. [2011]) and in non-encumbering forms (e.g. Google Glass, Lumus DK-32). However, to date no practical design has demonstrated both a wide field of view *and* low encumbrance in a single AR device.

The crux of the problem is that these requirements typically place opposing constraints on the optical hardware design. For example, optical see-through devices that place a beamsplitter embedded in a waveguide in front of the eye (e.g. Epson Moverio BT-100) have a field of view that increases with the thickness of the waveguide; in the case of the Epson device, the field of view is limited to 23° diagonally while keeping the device acceptably thin and light.

In contrast, we present a novel optical see-through near-eye display design that provides a wide field of view and supports a compact and lightweight form factor that approaches ordinary eyeglasses. We replace conventional optical approaches, such as waveguides and beamsplitters, with a design that combines simple hardware and lightweight computation. We avoid the need for any optical refractive, reflective, or diffractive components that could limit field of view, and use only two simple and readily manufactured hardware components: an LCD panel and a sparse array of small, bright point light sources, formed on a patterned edge-lit acrylic sheet, that we call *pinlights*. Our core innovation is the use of *defocused* point light sources coded through a transmissive spatial light

modulator (SLM) to form miniature, see-through, and therefore *imperceptible* projectors. These miniature projectors direct light into the lens of the eye through a *virtual aperture*, allowing their small image areas to be tiled to create an arbitrarily wide field of view. Software decomposes the target
5 image into a series of tiled sub-images (displayed on the SLM) that each correspond to a miniature projector with a virtual aperture. We demonstrate the feasibility of our approach through a real-time prototype display in the form factor of large glasses that offers a 110° diagonal field of view.

10 1.1 Contributions

We present a novel approach to see-through near-eye displays. Specific contributions include:

- 15 • the use of point light sources, coded with an LCD and placed *near the eye*, that act as *imperceptible, see-through* projectors
- the use of such projectors in a *tiled* configuration encoded with a *virtual aperture* to expand the FOV of the display
- the use of such tiled projection arrays in an alternative configuration to provide a *light field* over the eye, as a *see-through*
20 alternative to existing near-eye light field displays
- an example *hardware design* for creating transparent tiled projection arrays, described and evaluated in a prototype device

25 1.2 Benefits

The proposed design offers several benefits over existing see-through near-eye displays. A wide FOV is supported with no theoretical upper bound (or approaching 180° if the display components are planar), and a prototype achieving a 110° diagonal FOV is demonstrated. The design also supports a
30 lightweight, eyeglasses-like form factor and uses simple, low cost hardware components.

2 Related Work

Near-Eye See-Through Displays

5 Near-eye displays, particularly optical see-through systems, have experienced a groundswell of consumer enthusiasm over the last year, initiated in part by the joint introduction of Google Glass (narrow field of view AR) and Oculus Rift (low-cost yet immersive VR). However, the optical designs underpinning the majority of these commercially-announced devices
10 have been maturing over decades of research. Kress and Starner [2013] provide a concise survey of the state-of-the-art in near-eye displays. We briefly survey these systems, studying their benefits and limitations relative to our new pinlight projection system.

 Freeform optics innovate on the traditional beamsplitter approach to
15 achieve optical see-through, leveraging the complex, aspheric surfaces afforded by modern optical fabrication methods [Cakmakci et al. 2010; Cheng et al. 2011]. Rather than employing a planar combiner and separate relay lens elements, a single optical “prism” is manufactured to unify the functions of relaying, magnifying, and combining the virtual image.
20 Aberrations of the virtual and physical environments are corrected by jointly optimizing the optical surfaces. Freeform optics replace the bulk of head-mounted relay optics with precision-manufactured prisms; however, their FOV remains limited, with the volume of the prism growing proportionally to the target FOV. Waveguide-based designs can overcome this limitation:
25 temple-mounted projectors are used to shine light into a flat waveguide, where it travels by total internal reflection (TIR) to an *out-coupling element* that redirects the image to the viewer’s eye. Waveguide approaches are differentiated by the composition of the out-coupling (and associated in-coupling) elements. Systems such as the Lumus DK-32 and the Optinvent
30 ORA-S utilize a set of *cascaded extractors* comprising an array of precisely-aligned semi-reflective mirrors. Alternatively, diffractive optical elements have been successfully employed to achieve out-coupling, including grating patterns and more general volume holograms [Levola 2006]. The FOV of

such systems is restricted by the TIR angle supported by the waveguide, practically limiting systems at the moment to less than roughly 60°.

Our use of a direct-view LCD panel, with no additional relay, magnification, or combining optics, is shared by only a handful of near-eye
5 displays. The recently-announced Innovega iOptik display system uses a direct-view display and a custom contact lens. The contact lens employs polarization-selective filters and an embedded microlens to transform the viewer's accommodation range: the central portion of the pupil becomes
10 capable of focusing on the near-eye display (through the microlens), whereas the outer annulus retains the viewer's natural accommodation range. In a closely-related work, Maimone and Fuchs [2013] propose a near-eye display composed of compact stacks of 2-3 direct-view LCD panels. This multi-layered display presents a series of time-multiplexed attenuation patterns – at greater than the human flicker fusion threshold – creating a
15 near-eye light field display. Similar to our design, eye tracking significantly enhances resolution. We emphasize that the pinlight approach differentiates itself by eliminating the need for contact lenses or complex, multi-layered LCD panels.

20 **Coded Projections using Defocused Optical Elements**

Our development of near-eye coded pinlight projectors is related to defocused projection systems. In the computer graphics community, Mohan et al. [2009] present one of the earliest such designs; their “Bokode” system
25 uses a combination of a backlit, microprinted transparency covered with a microlens to project an image at optical infinity from an aperture of a few millimeters. A coded image is formed when observed with a defocused wide-aperture camera, allowing extremely compact substitutes for traditional 2D barcodes. Hiura et al. [2010] extend this approach to curved arrays of
30 Bokodes, which they dub “Krill-eye beacons” due to the optical similarity with refracting superposition compound eyes in decapods. In contrast to our system, these beacons rely on refractive lenses and are intended to be distantly located from any imager.

Pamplona et al. [2010; 2011] demonstrate near-eye applications of these principles to interactively assess the refractive errors of human subjects. In their system, a near-eye light field display is created by covering a microdisplay with either a microlens array or a pinhole grid to present test
5 patterns containing accommodation cues. Recently, Lanman and Luebke [2013] show that such systems can be optimized for general display applications, demonstrating lightweight, thin-form-factor virtual reality eyeglasses. We emphasize that, while sharing conceptual similarities, neither approach directly facilitates optical see-through applications:
10 refractive microlens arrays irrevocably distort the viewer's perspective.

We also find similarities with a specialized class of light field displays: those exploiting *parallax illumination*. In a related work, Son et al. [2007] substitute a 2D point light source (PLS) array for the microlenses and pinholes (or parallax barriers) routinely found within light field displays. As
15 with our pinlight projectors, multiview imagery is projected by displaying a coded array of elemental images on an LCD placed in front of the PLS array. We also find similarities in our approach to projector-based displays. Jurik et al. [2011] describe a light field display in which each projector in a dense array acts as a single display "pixel" with a high degree of angular variation.
20 We emphasize that, unlike pinlight displays, PLS arrays and projection arrays are designed to function within the accommodation range of the observer (e.g. as a desktop 3D display). Furthermore, we demonstrate architectures for making these arrays imperceptible in near-eye use. Instead of the LED array of Son et al. [2007], or the pico projectors of Jurik et al.
25 [2011], we use an edge-lit acrylic sheet with a pattern of microdivots.

3 System Overview

3.1 Introduction

30

Optical see-through near-eye displays place synthetic imagery over one's natural vision using a device placed closer than the eyes can focus. Such displays have two primary goals: (1) to adjust for the focal range of the

eye, while (2) preserving the ability to see the real world through the display. Displays using conventional optical approaches address these functions with additional components, such as lenses and beamsplitters. These components tend to add complexity and bulk to the design and limit the field
5 of view.

We take an optically simpler approach that avoids these components by designing a *highly directional* image source that emits light over a very narrow angle and specific orientation for each pixel. Thus, each image pixel acts as a “ray” source (within an approximation), rather than a point source.
10 With this design, the light emitted from each *individual* pixel of the image source is essentially non-divergent, and can enter the eye directly without corrective optics and regardless of eye focal state. We achieve such an image source by coding the light from a sparse array of point sources with a spatial light modulator. We must, however, account for this different image
15 formation method by preprocessing the image. To preserve the see-through capability, our design uses only transparent components, a see-through point light array and a transmissive SLM, placed directly in front of the eye. This avoids the need for any cumbersome or FOV-limiting components to combine the augmented image and see-through optical paths. In this way,
20 we follow the approach of Maimone and Fuchs [2013] who stacked transmissive SLMs for a see-through near-eye display. We add novelty by achieving transparency using components with small *visible* features ($\leq 100 \mu\text{m}$) that are *imperceptible when defocused*.

Figure 1A illustrates an exemplary point light source for use with
25 embodiments of the subject matter described herein. In Figure 1A, a backlight layer **100** comprises a rectangular acrylic sheet etched with a plurality of surface features **102** that act as point light sources. When backlight layer **100** is illuminated from an edge, light is emitted through surface features **102** but not between surface features **102**. The absence of
30 light between surface features **102** is caused by the flat surface and total internal reflection. In the illustrated example, backlight layer **100** is illuminated using an LED light source **104** for illustrative purposes. Because

backlight layer **100** is placed near the user's eye in operation, point light sources **102** will appear out of focus, as illustrated by window **106**.

Figure 1B illustrates a prototype of a near-eye see-through display according to an embodiment of the subject matter described herein.

5 Referring to Figure 1B, the prototype comprises an eyeglasses frame **108** designed to be worn by a user. Backlight layers **100** are mounted in eyeglasses frame **108** in the same places where corrective lenses would be mounted. Spatial light modulator layers **110**, which in the illustrated example are see-through liquid crystal displays, are also mounted within the user's
10 field of view. Spatial light modulator layers **110** encode the defocused point light sources **102** (also referred to herein as pinlights) to form a desired image on the user's retina.

In one embodiment of the subject matter described herein, only the encoded pinlights that contribute to the desired image are illuminated and
15 visible to the wearer. The defocused pinlights that do not contribute to the desired image may be deactivated (i.e. not illuminated) so that they do not project any light towards the eye. Alternatively, all of the pinlights can be illuminated regardless of the desired image content, in which case a see-through image is provided but some additional light is projected where there
20 is no desired image content.

Figure 1C illustrates an example of a see-through image superimposed on a real image viewed through the prototype illustrated in Figure 1B. In Figure 1C, the virtual see-through image comprises an image of a tie fighter from the movie, Star Wars. The real image comprises a view
25 of a room and a poster mounted on a wall in the room. As illustrated in Figure 1C, the synthetic image occupies a wide field of view with respect to the entire field of view of the user.

Figure 1D is an image comparing the field of view of the prototype display illustrated in Figure 1B (110°) and other commercial optical see-
30 through glasses. The field of view of the pinlights prototype illustrated in Figure 1B is 110°. The field of view of the Lumus DK-32, Meta pro is 40°, the field of view of the Epson Moverio BT-100 is 23°.

3.2 Coded Projection with a Single Pinlight

Image Formation

Our core approach is directly encoding light from a *defocused* point source placed near the eye (outside of the accommodation range), which we call a *pinlight*, with a transmissive SLM placed between the eye and the pinlight. This system acts as a miniature projector, which we call a *pinlight projector*, that directs light into the eye as illustrated in Figure 2. Assuming for simplicity that the pinlight and the pixels on the SLM are true mathematical points, each location on the SLM receives light from a single direction (a “ray”) that is modulated and then enters the eye. The set of all rays is refracted by the lens of the eye; however, since the rays originate from a single point their angular ordering is preserved, creating a “sharp” copy of the modulated image on the retina. Since the point source is nearer than the viewer’s minimum accommodation or focus distance, the image is not flipped by the eye, and thus the modulated image must be inverted along both axes. The image formed on the retina is “sharp” regardless of the focal state of the eye (much as with a camera with an small pinhole aperture); the eye’s focal state changes only the degree of refraction and therefore the scaling of the image formed. Note that the image produced by a pinlight projector is generally round, due to the shape of a human pupil, which adds complexity to optical design as described in Section 3.3. See Section 3.4.1 for details concerning the creation of real point sources with non-zero extent and handling changes in eye state. See-through ability is achieved through the use of transparent components; see Section 3.4.3 for details.

Projection Geometry

From Figure 2, it can be seen that the necessary diameter of modulation on the SLM a_m and the diameter of the image on the focus plane a_f for a *single* pinlight projector can be computed as:

$$a_m = a_e \left(1 - \frac{d_m}{d_p} \right), a_f = a_e \left(\frac{d_f}{d_p} - 1 \right) \quad (1)$$

given eye aperture diameter a_e , pinlight plane distance d_p , modulation plane distance d_m , and eye focus distance d_f . Likewise, the field of view θ_p through the single pinlight can be computed as:

$$\theta_p = 2 \tan^{-1} \left(\frac{a_e}{2d_p} \right) \quad (2)$$

The pinlight plane distance d_p and modulation plane distance d_m are the variables under the control of the display designer. From Equation 2, we observe then that the FOV through a single pinlight projector θ_p is increased by decreasing pinlight plane distance d_p . Given a selection of d_p , modulation plane distance d_m can be chosen to select the desired modulation scale on the SLM. However, for eye pupil diameter $a_e = 3$ mm, the pinlight plane set at a practical distance of $d_p = 25$ mm yields a FOV through the pinlight projector θ_p of only 6.9° . Obtaining a wide field of view of 100° would require an impractically close pinlight plane distance of $d_p = 1.26$ mm. However, we explore the use of multiple pinlight projectors to increase the field of view, as described in the following section.

3.3 Coded Projections using Tiled Pinlight Arrays

A single pinlight projector does not alone provide a useful field of view for an augmented reality display. We observe, however, that multiple pinlight projectors may be *tiled* to significantly increase the field of view. In this section, we describe various tiling configurations.

Ideal Tiling Geometry

When tiling pinlight projectors, we assumed that the pinlight plane now contains an *array* of point light sources, all of which are modulated by a

single SLM. Further, we assume that the pinlights emit light over a wide angle so that each is visible to the eye (but we are unconcerned with light rays that do not enter the eye). In this configuration, the pinlights can be tiled to an arbitrarily wide field of view (or approaching 180° if the pinlight array and SLM are restricted to planes) where the total display area is approximately proportional to the number of projectors used, subject to practical limitations on the emission angle of the pinlights and the size and supported viewing angles of the SLM. The tiling must satisfy two primary conditions: the eye focus plane must contain a *continuous* tiled image among all the projectors, and the modulated areas on the SLM must be *disjoint* among the projectors. We also aim to maximize resolution by using as much area on the SLM as possible. We first consider an *ideal* one-dimensional case, illustrated in Figure 3. Given an eye aperture a_e , eye focus distance d_f , and pinlight plane distance d_p , the optimal pinlight spacing s and modulation plane distance d_m are computed as:

$$s = a_e \left(1 - \frac{d_p}{d_f} \right) \quad \text{and} \quad d_m = \frac{a_e d_p}{a_e + s}. \quad (3)$$

This spacing ensures that neighboring view cones abut at the modulation plane and focus planes, providing a continuous image at the full resolution of the SLM. Note that the pinlights are placed sparsely (with spacing on the order of the eye aperture (pupil) size) (e.g., about 3 mm between pinlights or surface features **102** on backlight layer **100** illustrated in Figure 1A), so that the structure of an *array* of small pinlights will remain imperceptible when defocused. Also note that the display becomes thinner as it is moved nearer the eye (i.e., decreasing d_p decreases $d_p - d_m$).

The effective resolution r in terms of the preserved fraction of modulation plane resolution (by area) can be computed as:

$$r = \left(\frac{d_f (d_p - d_m)}{d_m (d_f - d_p)} \right)^2 \quad (4)$$

This equation provides the ratio of the width of a pixel projected onto the focus plane to the total width of the focus plane, squared to provide a ratio by area. Note that this equation assumes that the pinlight geometry is valid; the eye focus plane must contain a continuous tiled image, and the modulated areas on the SLM must be disjoint among projectors. In the ideal configuration, ratio r equals 1: the entire modulation plane has been used to form an image on the focus plane without redundancy. The horizontal field of view f_h from a point on the eye can also be computed as:

10

$$f_h = 2 \tan^{-1} \left(\frac{c}{2d_m} \right) \quad (5)$$

where c is the width of the modulation plane.

15 **Challenges for Practical Tiling**

Tiling has the potential to create a wide field of view display. However, in the *ideal* 1D case described above we have not considered several factors which must be addressed to create a practical *human-wearable* display:

20 • The ideal case can only be directly extended to 2D if the image areas created by the pinlight projectors can be tiled; however, a circular image area is created when projecting into the round human pupil, which cannot be tiled without the inclusion of gaps or overlapping areas.

25 • The ideal model assumes that the eye position is fixed relative to the display, an invalid assumption for a viewer wearing glasses. If the eye moves the image will circularly shift *within* the tiled sub-images corresponding to each pinlight projector, resulting in a corrupted image.

• The ideal model is affected by changes in pupil size and focal state, which are expected to change over time.

30

In the remainder of this section, we address items 1-3 under two alternative configurations. Item 4 is addressed in Section 3.4.5.

3.3.1 Tracked Virtual Aperture Configuration

Eye Tracking

5 In one alternative tiled configuration, we allow eye movement relative to the display by assuming that the position of the eye on the pupil plane is known (i.e. tracked) and that the image on the modulation plane is adjusted to account for the new eye position. As the eye moves, the view cones that corresponding to each pinlight projector (illustrated in Figure 3) shift and
10 intersect with a new portion of the intended image on the eye focus plane, which is then flipped and scaled appropriately to be encoded on the corresponding region of the modulation plane (see Section 3.4.4 for details). In this section, we assume theoretical error-free tracking without latency in sensing or display; in Section 3.3.2 we describe how to account for these
15 factors.

Virtual Eye Apertures

 Although eye tracking allows compensation for eye movements, it does not resolve the issue of how to tile the circular images formed by
20 individual pinlight projectors due to the round aperture of the eye. In particular, if the circular projectors are tiled without overlap, gaps will remain in the image, and if the circles overlap to fill the plane, the overlapping areas will have greater intensity than the non-overlapping areas (see Figure 6E). Our solution to create an evenly-toned image is to configure the pinlight
25 projectors so that they *minimally* overlap to fill the focus plane and to encode a *virtual aperture* over the modulation plane so that that light from the overlapping regions does not reach the eye. This process is illustrated in Figure 4. The virtual aperture has the effect of transforming the viewer's pupil into a shape that can be tiled (e.g. a rectangle or hexagon), as if
30 wearing a contact lens masked with such a shape.

Geometry

The ideal display geometry, given by Equation 3, is updated to support a *hexagonal* virtual eye aperture as follows.

$$s_{t_h} = \frac{\sqrt{3}}{2} a_e \left(1 - \frac{d_p}{d_f} \right), s_{t_v} = \frac{\sqrt{3}}{2} s_{t_h} \quad (6)$$

5

$$d_{m_t} = \frac{\frac{1}{2} \left(a_e + \frac{\sqrt{3}}{2} a_e \right) d_p}{\frac{1}{2} \left(a_e + \frac{\sqrt{3}}{2} a_e \right) + s_{t_h}} \quad (7)$$

This geometry assumes that the virtual aperture is encoded as a hexagon with vertical left and right sides and a pointed top, as seen in Figure 10B. Note that the horizontal pinlight spacing s_{t_h} and vertical spacing s_{t_v} are asymmetric and that odd pinlight projector rows should be offset by $\frac{s_{t_h}}{2}$ due to the staggered hexagonal packing of the plane. Also note the similarity to the geometry in the ideal case (Equation 3), except that pinlight spacing s has been decreased to allow the circular image areas of the pinlight projectors to overlap to cover the focus plane, and modulation plane distance d_m has been adjusted to allow space for the virtual aperture mask. In particular, a regular hexagon is inscribed into the circular area on the modulation plane that represents each pinlight projector, and d_{m_t} is set so that the projectors are positioned as closely as possible without intersecting the inscribed hexagons of neighboring projectors. This process causes a resolution loss as some of the modulation plane is now dedicated to providing an aperture mask rather than contributing to the virtual image. The resolution loss can be computed according to Equation 4. Equivalently, the effective resolution (by area) in a tracked virtual aperture configuration can be computed as the ratio of the area of the inscribed hexagon in a unit diameter circle $\left(\frac{3\sqrt{3}}{8} \right)$ with the area of the larger hexagon that would exactly

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tile the plane without the virtual aperture mask $\left(\frac{7\sqrt{3}+12}{32}\right)$, yielding effective resolution ratio r_t :

$$r_t = \frac{12\sqrt{3}}{12+7\sqrt{3}} \approx 86\%. \quad (8)$$

However, spatial resolution loss is very modest compared to existing near-eye light field displays (e.g. [Maimone and Fuchs 2013]) showing the benefit of a design that allocates nearly of all the display area to forming the image perceived by the user, through tracking. Also note that moving the modulation plane closer to the pinlight plane to accommodate the virtual aperture has the positive side effect of creating a slightly thinner display; e.g., an aperture $a_e = 3$ mm focused at $d_f = \infty$ with the pinlight plane placed at $d_p = 29$ mm now yields a device $d_{m_t} = 15$ mm away from the eye that is $d_p - d_{m_t} = 14$ mm thick (i.e. 1 mm thinner).

3.3.2 Untracked Light Field Configuration

Near-Eye Light Fields

In another alternative tiled projector configuration, the display is designed to generate a *light field* near the eye to allow additional capabilities. The display is designed so that the view cones between pinlight projectors *overlap* away from the display, allowing angular variation in the image among projectors. In particular, one can design the display to allow angular variation *around* the eye to create an *untracked* configuration, which we explore in this section. It is also possible to design the display to emit a light field with angular variation *over* the pupil (creating depth of field). For example, in one embodiment of the subject matter described herein, the point light sources and the spatial light modulator may be configured so that each point in the synthetic image reproduced by two or more modulated rays emitted by the spatial light modulator simultaneously enter a pupil of the user's eye so that the user receives focal depth cues.

Untracked Configuration

The tracked display configuration offers high spatial resolution, but the need for pupil tracking adds engineering complexity. An alternative display can be defined with an *eyeb*ox, a region in which the eye can move around while still seeing the complete intended image. Here, the display is configured to emit multiple light rays that appear to originate from each point on the eye focus plane, each of which is directed towards different regions of the eyebox, as illustrated in Figure 5. To maximize resolution, the display geometry minimizes the number of modulated rays emitted from each point on the eye focus plane with assurance that an eye placed anywhere in the eyebox will receive one such ray; Equations 6 and 7 take the following form in this configuration:

$$s_{u_h} = \frac{\sqrt{3}}{2} a_{e_m} \left(1 - \frac{d_p}{d_f} \right), s_{u_v} = \frac{\sqrt{3}}{2} s_{u_h}, d_{m_u} = \frac{a_{e_b} d_p}{a_{e_b} + s_{u_h}} \quad (9)$$

Horizontal pinlight spacing s_{u_h} and vertical spacing s_{u_v} are defined with respect to a minimum eye aperture a_{e_m} ; a viewer with a smaller aperture will perceive gaps in the image. Modulation plane distance d_{m_u} is defined with respect to a constrained window around the eye a_{e_b} , creating an eyebox of size $a_{e_b} - a_e$. Unlike a conventional display, each ray in the eyebox can be modulated individually, allowing different images to be perceived with eye movement and without tracking. The display is considerably thinner in this configuration; an eye with minimum aperture $a_{e_m} = 3$ mm and eyebox of $a_{e_b} - a_e = 7$ mm (when $a_e = a_{e_m}$) focused at $d_f = \infty$ with the pinlight plane at $d_p = 18.9$ mm yields a device $d_{m_u} = 15$ mm from the eye that is $d_p - d_{m_u} = 3.9$ mm thick.

25

3.4 Practical Implementation Details

In this section, we address issues of realizing a display based on the tiled pinlight projector method that is practical for human viewers.

5

3.4.1 *Creating Point Light Sources*

Requirements

To create point light sources for pinlight projectors, we note three
10 primary requirements. First, the pinlight sources should be very bright, i.e. the total light emitted should be on par with a normal display panel, but concentrated into the much smaller area of a sparse grid of dots. Second, the emission area of each pinlight should be very small (i.e. on the order of the size of a pixel on the SLM) as the image formed is essentially convolved
15 with the pinlight shape. To maximize resolution, the effective aperture size of the SLM pixels (with consideration for the pixel fill factor) plus the size of the pinlight should be less than or equal to the pixel pitch of the SLM. Finally, the pinlight array should be highly transparent and any of the structures composing the pinlight array should be small enough as to be imperceptible
20 when defocused.

Implementation

As stated above with regard to Figure 1A, our prototype
implementation is a waveguide (an acrylic sheet) that is etched with tiny
25 divots and edge illuminated with LEDs, as illustrated in Figure 6A-6F. Light from the LEDs is channeled through the waveguide to the opposite side except where it encounters the divots, which scatter light and cause bright spots to appear. The divots were etched using a needle attached to the moving robotic platform, which was programmed to create a staggered
30 pinlight array according to Equation 6. The etched features may be visible, but the pinlight array appears completely clear when held near the eye, out of focus. The divots may also be created through a process of laser drilling.

More particularly, as illustrated in Figure 6A, a backlight layer **100** is formed by creating small divots on an acrylic sheet using a needle attached to a robotic arm **112**. Figure 6B illustrates backlight layer **100** with an array of visible divots when viewed at the focal distance of a human eye. As
5 illustrated in Figure 6C, when viewed with a camera with an aperture and focus similar to the human eye, the divots appear imperceptible and see-through. As illustrated in Figure 6D, when viewed from the side and illuminated with a light source, bright spots appear on the waveguide. In Figure 6E, when the bright spots are defocused near the camera, the
10 pinlights form discs that tile.

Figure 6F is a side view of backlight layer **100**. In Figure 6F, light from a light source **114** enters backlight layer **100** through an edge of backlight layer **100**. Because of total internal reflection, light rays from the light source do not exit backlight layer **100** from the front face except through
15 divots **102**. As stated above, divots **102** may be spaced from each other with an inter-divot spacing of about the same size as the human eye aperture (e.g., about 3mm).

Note other possibilities for creating an array of transparent light sources: transparent emissive displays (e.g. transparent OLEDs), LED or
20 laser chips mounted on a transparent conductive substrate (e.g. ITO coated glass), fiber optics, holograms, and quantum dots.

3.4.2 Modulating Light Sources

25 An SLM intended for a pinlight projector display must work in a transmissive mode and should have high transmittance, a wide viewing angle, high contrast, and should minimally diffract light. In our implementation, we selected an LCD microdisplay with high transmissivity and pixel density. To minimize the diffraction and light loss through the
30 display caused by color filters, a monochrome panel may be used and operated in conjunction with a color sequential pinlight array. Hardware implementation details are described in Section 4.1.

3.4.3 *Optimizing See-Through Capability*

To achieve a see-through capability, it is assumed that the SLM and pinlight array are effectively transparent when defocused near the eye. Note, however, two complicating factors. First, light from the environment may permeate the SLM in addition to illumination from the pinlights, causing a soft defocused glow around the synthetic image (see Figure 10C). Second, light from the environment only reaches the eye through the defocused mask on the SLM, causing a soft, uneven coloring of the environment and allowing little light to reach the eye in areas where there are no synthetic objects (see Figure 10D). To mitigate these issues, we may rapidly alternate between displaying an augmented image with the pinlights on (see Figure 10D), and displaying a occlusion mask of the augmented image with the pinlights off (which appears defocused, see Figure 11D). This allows light from the environment to reach parts of the display where no augmented imagery is shown and reduces the apparent soft glow around the augmented images (see Figure 10E).

3.4.4 *Creating Modulation Masks*

To create the modulation masks to display on the SLM, the virtual scene is projected through the pinlights onto the modulation layer with respect to the eye. We implement this process in software by rendering the virtual scene with a camera that uses an off-axis projection frustum defined by the eye and each pinlight; this process is repeated for each pinlight. If the scene is a simple 2D plane at the eye focus distance (rather than an arbitrary light field), this process is performed more efficiently by finding the intersection of the camera frustum and the focus plane and transferring a flipped and appropriately scaled copy of the image region onto the correct region of the modulation plane. For images representing occlusion masks, we simply draw an unmodified copy of the image on the modulation plane, which appears defocused when viewed. Example modulation and occlusion masks are shown in Figures 11A and 11C.

3.4.5 Changes in Eye State

Although accommodating the display for eye movement was
5 discussed in Section 3.3, the eye may change in other ways that may affect
the display; notably the pupil size or focal state may change.

Handling Change in Pupil Size

In the tracked configuration (Section 3.3.1), we assumed that the eye
10 aperture size was fixed in Equation 6. We can account for a dynamic
aperture size using one of four methods. First, the display geometry can be
configured for the maximum allowable aperture size and a *virtual aperture*
(see Section 3.3.1) can be created with the minimum allowable size. This
allows only a smaller central area of the pupil to receive light as the pupil
15 size changes, but will cause a resolution loss proportional to the ratio of the
largest and smallest apertures. Second, the display could be configured with
a small eyebox sufficient to allow the pupil size to expand beyond a
minimum size. This approach also results in a similar loss in resolution but
the additional of a small eyebox also helps compensate for tracker error and
20 latency. Third, the display could be outfitted with a *dynamic* pinlight array
(e.g. a transparent OLED display) that can adjust the spacing of the pinlights
according to tracked pupil sizes. Finally, the amount of light reaching the
eyes could be controlled in an active loop by the SLM and/or pinlight array in
an attempt to control pupil size to a predetermined size. The display could
25 also simply be set sufficiently bright to force the pupils to contract to near
their minimum size. However, note other factors than lighting may affect
pupil size. In the untracked configuration (Section 3.3.2), variable aperture
sizes are already considered in Equation 9.

30 Eye Focus

In a tiled pinlight projector display, changes from the expected eye
focus do not cause the image to become appreciably “blurred”, but rather
change the scaling of the tiled sub-images among the various projectors so

that they expand or contract, causing tile gaps or overlaps to occur in some cases. This is expected to appear less natural to the user than normal focal blur. However, the change in scaling is small unless the viewer is focused at very close range; e.g. the change in scaling from a distance of 1 m to infinity is $\leq 3\%$ in a typical display (see Equation 6). Gaps caused by nearer than expected focus can be avoided by configuring the pinlight projectors so that they slightly overlap.

4 Implementation

4.1 Hardware

To test our design experimentally, we created a prototype device that operates in the “tracked” configuration (see Section 3.3.1), but with the use of a camera in a known location rather than a human eye. Our prototype device consists of two main optical components: LCDs (Sony LCX017, 36.9 x 27.6 mm active area, 1024x768 pixels, 705 dpi, 60 Hz, monochrome) and a waveguide pinlight array that was constructed as described in Section 3.4.1 (1 mm thick, 1.8 mm horizontal pinlight pitch) with RGB LED color sequential illumination. The modulation plane and pinlight plane were spaced at a distance of $d_p - d_m = 13.5$ mm, creating an optical assembly with a total thickness of 15.5 mm including component thickness and 10.5 mm of empty space. The components were mounted in a 3D printed plastic eyeglasses frame. See photos in Figure 1B and Figure 7. The bulky components on the far left and right of the glasses house an LCD adapter board that can be removed in a future device.

In Figure 7, backlight layer **100** is mounted to eyeglasses frame **108**. Light sources **114** comprise red, green, and blue (RGB) LED arrays. Spatial light modulator **110** is mounted optically in front of backlight layer **100** and in the illustrated example comprises a transparent LCD. An adaptor board **116** and housing provides an electrical interface to the LCD panel.

The display was tested using a camera that approximated a human eye (PointGrey Flea2 camera body with a Fujinon F1.2, 2.3 mm aperture

lens). The camera was mounted behind the display (see Figure 8) at a distance that approximated a human wearing eyeglasses (i.e. a camera center of projection to modulation plane distance of $d_m = 16$ mm). More particularly, in Figure 8, camera **118** is mounted on the right-hand side of eyeglasses frame **108** behind its respective spatial light modulator **110**. An image taken through camera **118** is shown in Figure 1D. We did not implement eye tracking, but assumed the camera was in a known position behind the display. The field of view of the display through the camera is $\approx 110^\circ$ diagonally, limited by the camera's field of view and a cropping of the top of the camera image to remove portions of the LCD with poor viewing angles. The FOV was measured by placing a protractor **120** at the camera's center of projection as shown in Figures 8 and 1D.

An Arduino microcontroller board and transistor circuit were used to drive the RGB LEDs in a color sequential mode that was synchronized to the monochrome display. A occlusion mask sub-frame was also included to improve the see-through ability (see Section 3.4.3). The LCD panels were controlled by an externally housed driver board connected by a DVI link to an Intel Core i7 PC with an NVIDIA GTX 580 GPU running Linux.

4.2 Software

Real-time tiled imagery for the prototype display was generated with an OpenGL/GL Shader Language based program using the fast image transfer method described in Section 3.4.4. Computation times for generating the tiled images given the target image were 1-2 ms per frame. The program also decomposed the image into color channels for color sequential operation and adjusted the image to compensate for poor LCD contrast at wide angles. Simulated images were generated by drawing the modulation plane image and a grid of pinlight dots at their apparent positions with respect to a virtual camera placed at the eye position. Images were summed over a densely sampled set of positions over a round camera aperture that matched the diameter of the intended viewer.

5 Experimental Assessment

5.1 Simulated Results

5 To evaluate the theoretical performance of the proposed display design, we simulated various tiled pinlight projector configurations as described in Section 4.2 with a modulation plane that matched the specifications of our prototype LCD panel (see Section 4.1).

The following configurations were tested: (1) a tracked virtual aperture
10 configuration of $d_p = 29$ mm and $d_m = 15$ mm, (2) an untracked, small eyebox configuration of $d_p = 22.8$ mm, $d_m = 15$ mm, and $a_{e_b} = 5$ mm, and (3) a untracked larger eyebox configuration of $d_p = 18.6$ mm, $d_m = 15$ mm, and $a_{e_b} = 11$ mm. All configurations were simulated with an eye pupil size of $a_e = 3$ mm focused at a distance of $d_f = \infty$. Note that the tracked
15 configuration is similar to that used by our prototype display. The untracked, small eyebox configuration provides a miniature eyebox of $a_{e_b} - a_e = 2$ mm that could be used to compensate for tracker error and latency and pupil size variation.

Results are shown in Figure 9. More particularly, in Figure 9, the
20 inset images of the word "field" show magnified regions of the display. The top left image in Figure 9 is a reference image used as a target for simulation. The top right image in Figure 9 is a tracked configuration simulation. The bottom left image in Figure 9 illustrates an untracked configuration simulation (small eyebox). The bottom right image in Figure 9
25 illustrates results for an untracked configuration (large eyebox). The tracked virtual aperture simulation may be compared to the result achieved on our prototype display in Figures 12C and 12D. More particularly, Figures 12A-12D illustrate example images taken through the prototype display illustrated in Figure 1B. Figure 12A illustrates a user interacting with a virtual teapot.
30 Figure 12B illustrates a virtual image of a Darth Vader's tie fighter superimposed on the image of a room. Figure 12C is an image of text

displayed to fill the entire field of view. Figure 12D is a magnified region of the image from Figure 12C which represents a horizontal field of view of approximately 12°.

5 5.2 Prototype Display Results

To evaluate real-world performance, we also tested our tiled pinlight projector design using a hardware prototype with a camera placed behind the display. The hardware prototype was configured in the tracked virtual aperture configuration (see Section 3.3.1) with the assumption that the eye position was known using a camera placed in a fixed position. See Section 4.1 for full specifications.

Figure 10 shows the steps of image formation on our prototype. The image begins as overlapping defocused discs (Figure 10A) from the pinlight array which are converted to a plane of abutting hexagonal tiles through the encoding of a virtual aperture on the modulation plane (Figure 10B). An augmented image is then encoded in the modulation plane, which appears defocused when viewed with unstructured illumination from the scene (Figure 10C). When illuminated, the strongly directional light from the pinlight array causes a focused augmented image to appear, although the dark regions of the modulation mask cause the background to appear dark, except for a glowing region around the virtual image (Figure 10D). When an occlusion mask sub-frame is included with the pinlight array off, the see-through ability is improved (Figure 10E).

Figure 11 shows the inputs to the prototype display and the captured outputs when the display is operated in a color sequential mode with an occlusion mask sub-frame. During each color sub-frame, an encoded image is sent to the display's LCD panel (Figure 11A), which appears as Figure 11B when viewed through the display. During each occlusion mask sub-frame, the backlight is disabled and an occlusion image is sent to the LCD (Figure 11C), which appears defocused through the display (Figure 11D). The final perceived image is the integration of the color and occlusion mask

sub-frames (Figure 11F), which can be compared to the theoretical performance of the display through simulation (Figure 11E).

Figure 12 shows the display generating imagery for a variety of augmented reality scenarios: a gesture based interaction (Figure 12A),
5 visualization of a detailed model (Figure 12B), and display of overlaid text (Figure 12C). Note that Figure 12C shows the display utilizing its entire field of view of approximately 110° diagonally. Figure 12D shows a magnified region of Figure 12C which can be compared to the similar simulated case in Figure 9 (top right).

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6 Additional Details

Figure 13 is a schematic diagram of a near-eye see-through display according to an embodiment of the subject matter described herein. Referring to Figure 13, point light sources (not shown) on backlight layer **100**
15 pass through spatial light modulator **110** where they are modulated as described above to produce augmented image rays which enter the human eye through pupil **122**. An optional shutter **124** may be located behind backlight layer **100** to allow viewing of real scene **126** during part of a viewing cycle and to view only a virtual image displayed by spatial light
20 modulator **110** during a virtual image display cycle.

As described above, near-eye see-through displays are designed to be worn by the user so that the user can see a synthetic image superimposed over their view of their real environment. Some existing near-eye see-through displays suffer from a narrow field of view limitation inherent
25 in their designs. For example, near-eye see-through displays that relay an image from a small display to the eye through a waveguide are limited to a narrow field of view. When limited to a narrow field of view, spatially aligning synthetic objects to real objects is ineffective, as the narrow superimposed region changes as the user's head moves.

30 The subject matter described herein includes a near-eye optical see-through display that uses an array of point light sources located behind a spatial light modulator (SLM) to display an in focus image with a wide field of view at the pupil location. The geometry of the display shown in the

attached drawing is such that each pixel on the SLM is illuminated by light emanating from only a single point light source. As a result, the display forms a distant, in focus image to the user, although the display components are placed closer than the eyes can focus.

5 In some embodiments, the point light sources can be LEDs or OLEDs. In an alternate implementation (described above), the point light sources may be bright spots formed by creating scattering or light redirecting features on the surface of an illuminated waveguide. For example, backlight layer **100** illustrated in Figure 13 may include one or more light sources that
10 illuminate the edge(s) of a waveguide. The waveguide may include etched features that appear as point light sources that illuminate the SLM layer as described above with respect to Figures 6A-6F.

As stated above, a near-eye see-through display according to an embodiment of the subject matter described herein includes a compact form
15 factor and yields a wide field of view. Figure 14 illustrates another prototype of a near-eye see-through display according to an embodiment of the subject matter described herein. Referring to Figure 14, the display includes an eyeglasses frame **108A**. Backlight layers **100** are mounted in each eye frame. Spatial light modulators **110** are mounted behind each backlight
20 layer **100**. Shutter **124** is omitted as shutter **124** is an optional feature.

Figure 15 is a block diagram illustrating an exemplary system for displaying virtual images on a near-eye see-through display according to an embodiment of the subject matter described herein. Referring to Figure 15, the system includes a backlight layer **100**, a spatial light modulator **110**, and
25 a light source **114** as described above. In addition, if eye-tracking is implemented, the system may include an eye tracker **124** that tracks movements of the user's eyes. Eye tracker **124** may be a camera or other type of optical sensor capable of tracking pupil size changes and movements. A modulation and illumination controller **126** controls spatial
30 light modulator **110** and light source **114** so that desired virtual images are displayed in the user's field of view. Modulation and illumination controller **126** may be implemented in software executed by a processor **128**.

Alternatively, modulation and illumination controller **126** may be a hardware or firmware component.

As stated above, the displays described herein are capable of tiling light emanating from the pinlight projectors to achieve an arbitrarily wide field of view. In one embodiment, light emanating from the pinlight projectors can be tiled to produce a field of view of 60° or greater, in contrast with conventional near-eye displays that only achieve a field of view of less than 60° for synthetic images. While the subject matter described herein is capable of displaying synthetic images across a wider field of view than existing display systems, the light emanating from the pinlight displays can also be tiled to achieve fields of view narrower than 60° without requiring the complex optics of existing systems.

Figure 16 is a flow chart illustrating an exemplary process for displaying virtual images on a near-eye see-through display according to an embodiment of the subject matter described herein. Referring to Figure 16, in step **100**, point light sources on a backlight layer are illuminated. For example, point light sources on an acrylic sheet may be illuminated from edge mounted light sources. Alternatively, a see-through LED display may be used to implement the point light sources. In step **102**, light from the point light sources is modulated using a spatial light modulator to display a synthetic or virtual image superimposed on the user's view of a real scene. The modulation may be performed as described above such that a desired object being displayed is tiled to fill the field of view of the user.

In step **104**, if eye monitoring is implemented, control proceeds to step **106** where pupil movement and changes in pupil diameter are monitored. In step **108**, the modulation is continually adjusted to account for pupil changes. Monitoring eye movement and pupil diameter changes and adjusting the displayed images to account for these changes is described above with respect to Figure 3.

If eye monitoring is not implemented, redundant information is displayed to account for pupil changes, as indicated by block **110**. Displaying redundant information could account for pupil changes is described above with respect to Figure 5.

The disclosure of each of the following references is hereby incorporated herein by reference in its entirety.

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References

BENOÎT-PASANAU, C., GOUDAIL, F., CHAVEL, P., CATO, J.-P., AND BALLEST, J. 2010. Minimization of diffraction peaks of spatial light modulators using Voronoi diagrams. *Opt. Express* 18, 14, 15223-15235.

15

BROWN, M., MAJUMDER, A., AND YANG, R. 2005. Camera-based calibration techniques for seamless multiprojector displays. *Visualization and Computer Graphics, IEEE Transactions on* 11, 2 (March), 193-206.

20

CAKMAKCI, O., THOMPSON, K., VALLEE, P., COTE, J., AND ROLLAND, J. P. 2010. Design of a free-form single-element head-worn display. *Proc. SPIE 7618, Emerging Liquid Crystal Technologies V*, 761803-761803-6.

25

CHAING, H.-C., HO, T.-Y., AND SHEU, C.-R., 2005. Structure for reducing the diffraction effect in periodic electrode arrangements and liquid crystal device including the same. US Patent. US 6977705.

30

CHENG, D., WANG, Y., HUA, H., AND SASIAN, J. 2011. Design of a wide-angle, lightweight head-mounted display using free-form optics tiling. *Opt. Lett.* 36, 11 (Jun), 2098-2100.

30

HAGOOD, N., BARTON, R., BROSNIHAN, T., FIJOL, J., GANDHI, J., HALFMAN, M., PAYNE, R., AND STEYN, J. L. 2007. 35.5I: Late-news paper: A direct-view mems display for mobile applications. *SID Symposium Digest of Technical Papers* 38, 1, 1278-1281.

- HIURA, S., MOHAN, A., AND RASKAR, R. 2010. Krill-eye: Superposition compound eye for wide-angle imaging via grin lenses. *IPSN Transactions on Computer Vision and Applications*, 186-199.
- 5 JURIK, J., JONES, A., BOLAS, M., AND DEBEVEC, P. 2011. Prototyping a light field display involving direct observation of a video projector array. In *IEEE International Workshop on Projector-Camera Systems (PROCAMS)*.
- 10 KRESS, B., AND STARNER, T. 2013. A review of head-mounted displays (HMD) technologies and applications for consumer electronics. In *Proc. SPIE*, vol. 8720.
- LANMAN, D., AND LUEBKE, D. 2013. Near-eye light field displays. 15 *ACM Trans. Graph.* 32, 6 (Nov.), 220:1–220:10.
- LEVOLA, T. 2006. Diffractive optics for virtual displays. In *Journal of the Society for Information Display*.
- 20 MAIMONE, A., AND FUCHS, H. 2013. Computational augmented reality eyeglasses. In *Mixed and Augmented Reality (ISMAR), 2013 IEEE International Symposium on*, 29–38.
- 25 MOHAN, A., WOO, G., HIURA, S., SMITHWICK, Q., AND RASKAR, R. 2009. Bokode: Imperceptible visual tags for camera based interaction from a distance. In *ACM SIGGRAPH 2009 Papers*, ACM, New York, NY, USA, SIGGRAPH '09, 98:1-98:8.
- 30 PAMPLONA, V. F., MOHAN, A., OLIVEIRA, M. M., AND RASKAR, R. 2010. Netra: Interactive display for estimating refractive errors and focal range. In *ACM SIGGRAPH 2010 Papers*, ACM, New York, NY, USA, SIGGRAPH '10, 77:1–77:8.

PAMPLONA, V. F., PASSOS, E. B., ZIZKA, J., OLIVEIRA, M. M., LAWSON, E., CLUA, E., AND RASKAR, R. 2011. Catra: Interactive measuring and modeling of cataracts. In *ACM SIGGRAPH 2011 Papers*, ACM, New York, NY, USA, SIGGRAPH '11, 47:1–47:8.

5

SON, J.-Y., SAVELJEV, V. V., KIM, D.-S., KWON, Y.-M., AND KIM, S.-H. 2007. Three-dimensional imaging system based on a light-emitting diode array. *Optical Engineering* 46, 10, 103205-103205-4.

10 ŚWIRSKI, L., BULLING, A., AND DODGSON, N. A. 2012. Robust real-time pupil tracking in highly off-axis images. In *Proceedings of ETRA*.

TRAVIS, A., LARGE, T., EMERTON, N., AND BATHICHE, S. 2013. Wedge optics in flat panel displays. *Proceedings of the IEEE* 101, 1, 45–
15 60.

It will be understood that various details of the presently disclosed subject matter may be changed without departing from the scope of the
20 presently disclosed subject matter. Furthermore, the foregoing description is for the purpose of illustration only, and not for the purpose of limitation.

CLAIMS

What is claimed is:

1. A near-eye optical see-through display comprising:
 - 5 a backlight layer including a plurality of point light sources; and
 - a spatial light modulator (SLM) layer for modulating light from the point light sources, the spatial light modulator layer being located in an optical path between the point light sources and a user's eye, the spatial light modulator layer including pixels that are controllable to modulate the light from the point light sources such that light that impacts a user's eye has a desired intensity and color to display a synthetic image, wherein at least a portion of the backlight layer and at least a portion of the SLM layer are optically transparent to allow a user to view a real scene through the SLM layer and the backlight layer such that the synthetic image appears to be overlaid on a view of real scene, and wherein each pixel in the SLM layer modulates only a portion of the light emanating from the point light sources and entering the user's eye such that the synthetic image appears to be in focus to the user's eye.
- 10 2. The display of claim 1 wherein the point light sources comprise light emitting diodes.
3. The display of claim 1 wherein the point light sources comprise organic light emitting diodes.
- 15 4. The display of claim 1 wherein the point light sources comprise scattering or light redirecting features created on an illuminated waveguide.
- 20 5. The display of claim 1 comprising a shutter located on a scene side of the backlight layer, the shutter being controllable to be closed during a display phase in which the synthetic image is displayed on the
- 25
- 30

backlight layer and open during a see-through phase in which the synthetic image is not displayed on the backlight layer.

- 5 6. The display of claim 4 wherein the pixels on the SLM layer are controllable to allow rapid alternation between the display and see-through phases so that the synthetic image will appear to be overlaid on the real scene.
- 10 7. The display of claim 1 wherein the SLM layer comprises a liquid crystal display (LCD).
- 15 8. The display of claim 1 wherein the SLM layer is spaced from the point light sources such that each pixel on the SLM layer seen over the area of a pupil of the user's eye is illuminated by only a single light source.
- 20 9. The display of claim 1 comprising an eyeglasses frame, wherein the backlight layer and the SLM layer are mounted to the eyeglasses frame.
- 25 10. The display of claim 1 wherein the point light sources comprise features on or in a surface of sheet waveguide.
- 30 11. The display of claim 10 wherein the features form a two-dimensional array of the point light sources that are spaced from each other by a distance that is based on the size of an aperture of a human eye.
12. The display of claim 10 wherein the features are configured to create a tiled display of the synthetic image across a desired field of view of the user.
13. The display of claim 12 wherein the desired field of view is at least about 60°.

14. The near-eye see-through display of claim 1 comprising:
an eye monitor for tracking changes in eye position and pupil aperture size; and
an illumination and modulation controller for adjusting at least one of
5 the spatial light modulator or illumination of the backlight layer based on the changes in eye position or pupil aperture size.
15. The display of claim 1 comprising an illumination and modulation controller configured to control the spatial light modulator and/or
10 illumination of the backlight layer to display redundant information to account for changes in a viewer's eye.
16. The display of claim 1 wherein the spatial light modulator is configured to rotate the synthetic image to account for rotation
15 performed by a user's eye.
17. A near-eye optical see-through display comprising:
a display frame for mounting the display near a user's eye;
a backlight layer mounted to the display frame and including a
20 two-dimensional array of point light sources;
a spatial light modulator layer mounted to the display frame and for modulating light from the point light sources, the spatial light modulator being located in an optical path between the point light sources and a user's eye, the spatial light modulator layer being
25 controllable to modulate light from the point light sources to display a synthetic image overlaid on a view of a real scene through the user's eye; and
a modulation and illumination controller for controlling illumination of the backlight layer and modulation performed by the
30 spatial light modulator.
18. The display of claim 17 comprising a sensor for sensing changes in pupil position or size and wherein the modulation and illumination

controller is configured to adjust display of the synthetic image based on the changes in pupil position and size.

- 5 19. The display of claim 17 wherein the modulation and illumination controller is configured to display redundant information of the synthetic image to account for changes in pupil size and position.
- 10 20. The display of claim 17 wherein the modulation and illumination controller is configured to control the spatial light modulator to tile light emanating from the point light sources to produce the synthetic image across the horizontal field of view.
- 15 21. The display of claim 17 wherein the backlight layer comprises a sheet waveguide and wherein the point light sources comprise features formed in or on a surface of the sheet waveguide.
22. The display of claim 17 wherein the backlight layer the point light sources comprise optical fibers.
- 20 23. The display of claim 17 wherein point light sources comprise quantum dots.
24. The display of claim 17 wherein the point light sources comprise holograms.
- 25 25. The display of claim 17 wherein the point light sources and the spatial light modulator are configured so that each point in the synthetic image reproduced by two or more modulated rays emitted by the spatial light modulator simultaneously enter a pupil of the user's eye
- 30 so that the user receives focal depth cues.

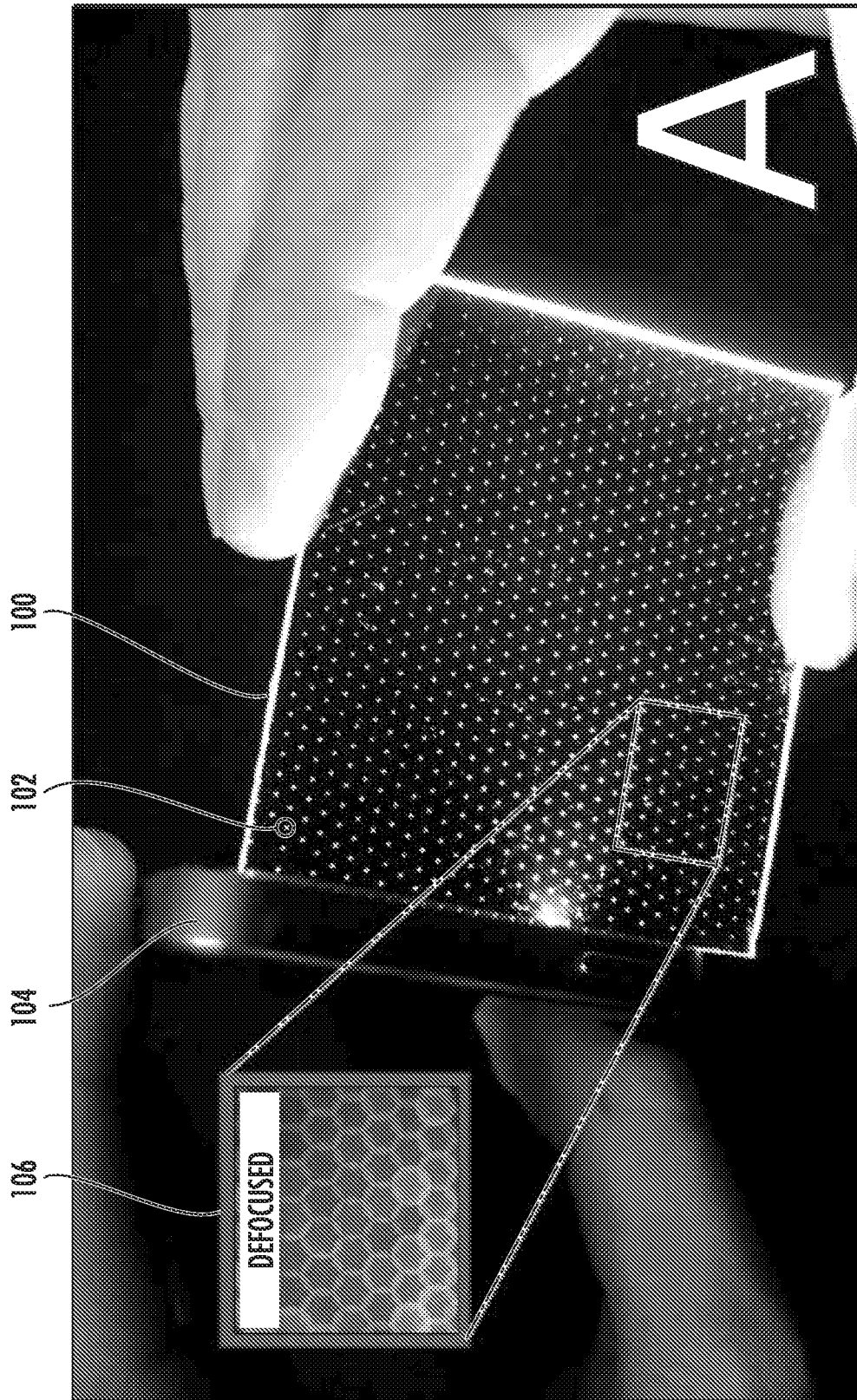


FIG. 1A

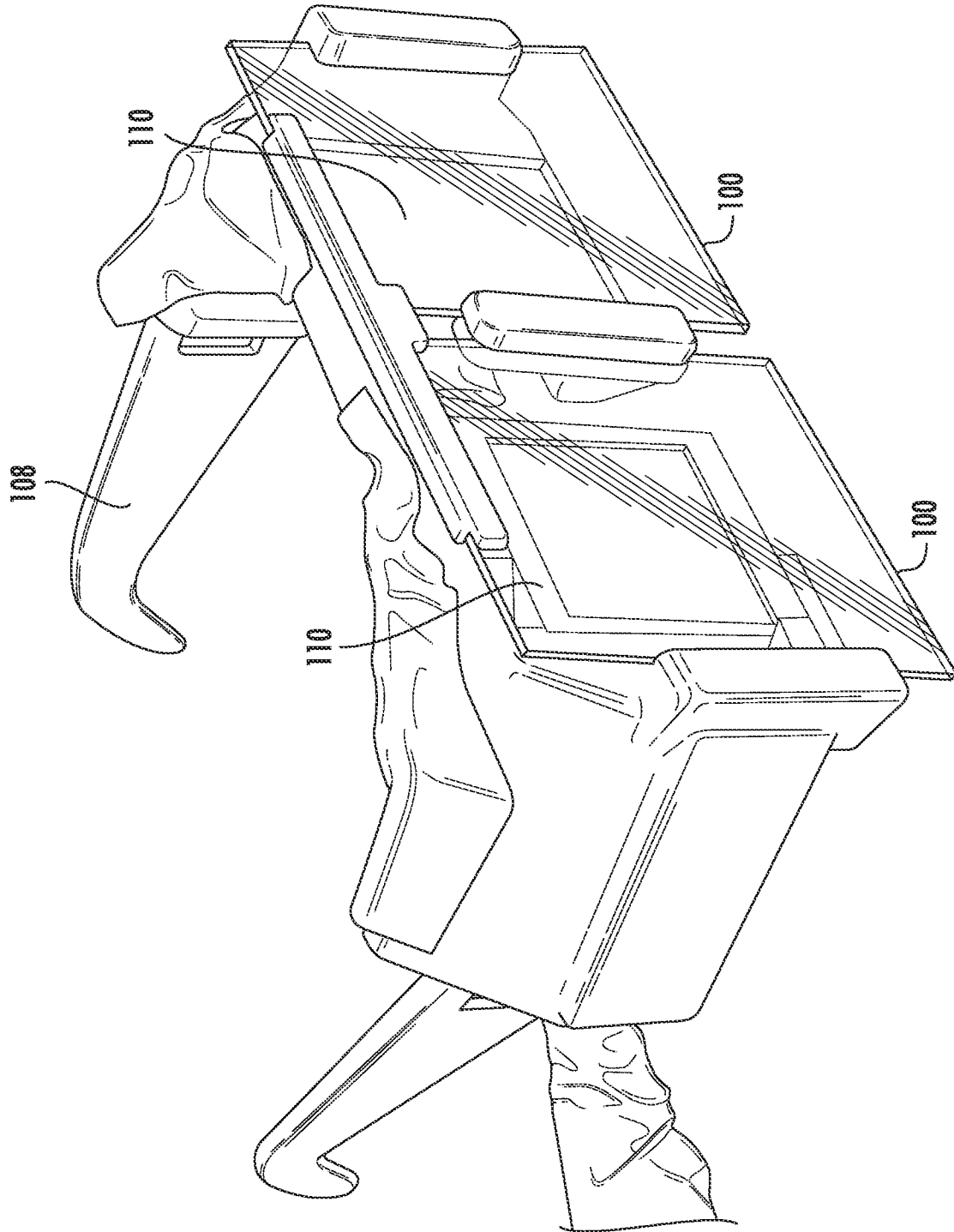


FIG. 1B



FIG. 1C

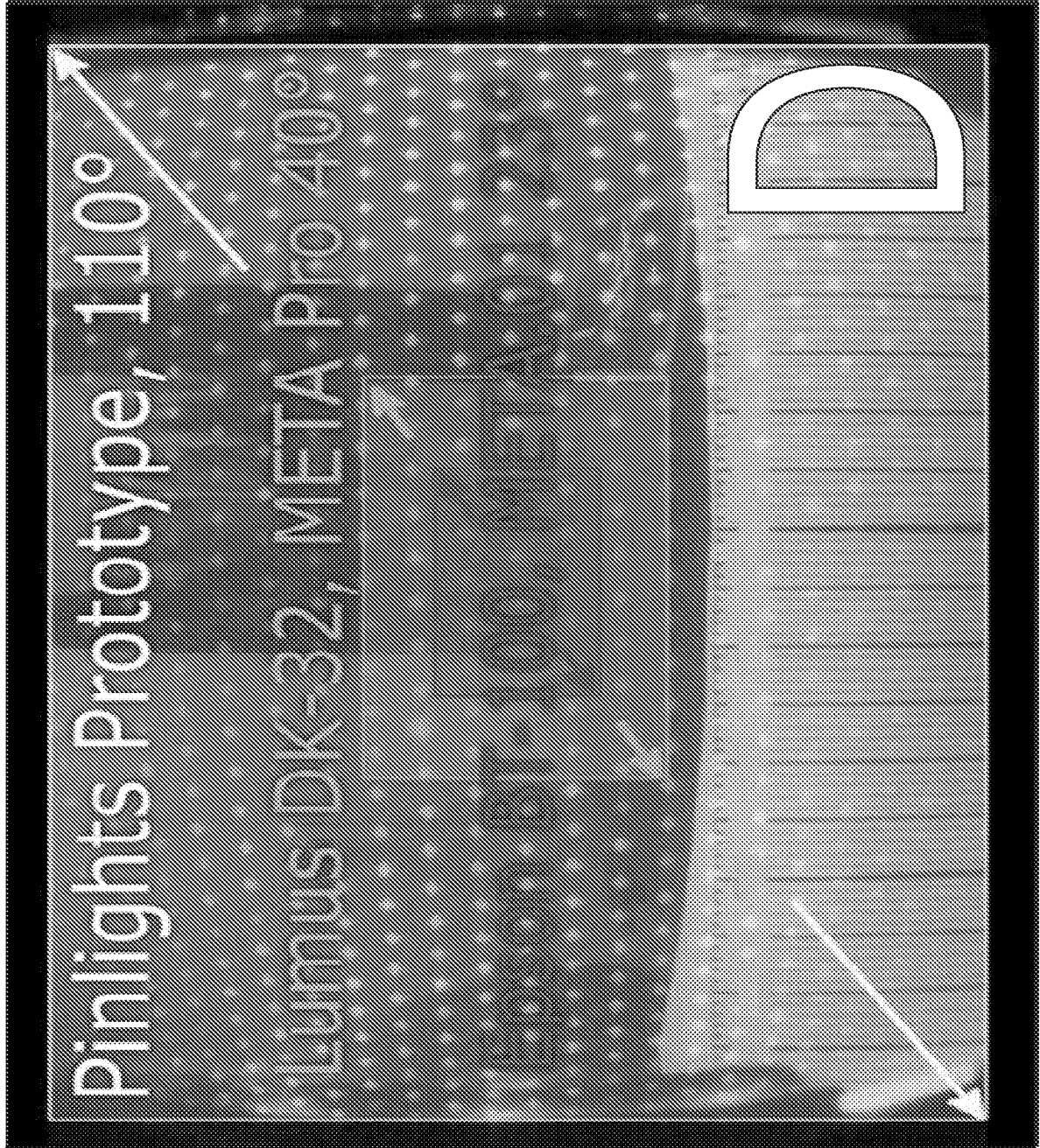


FIG. 1D

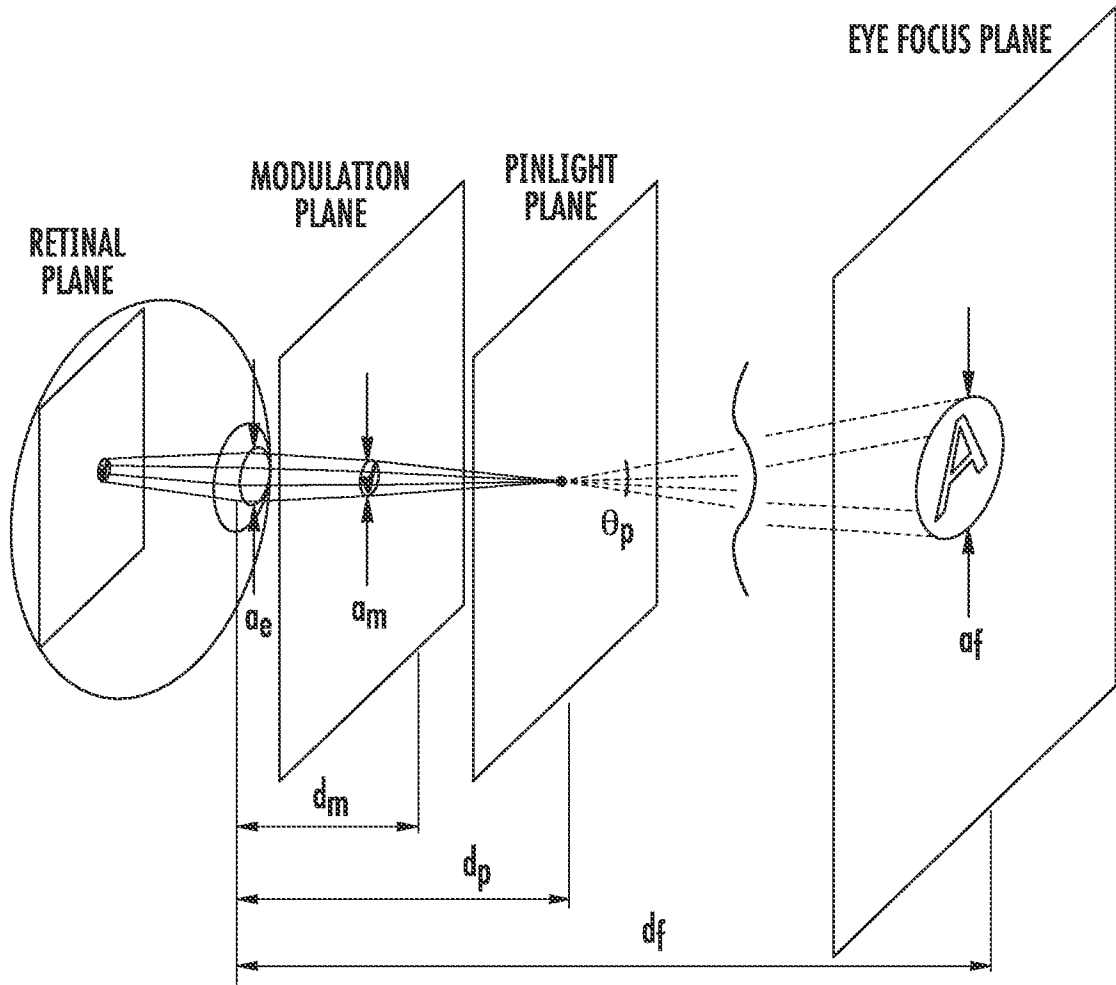


FIG. 2

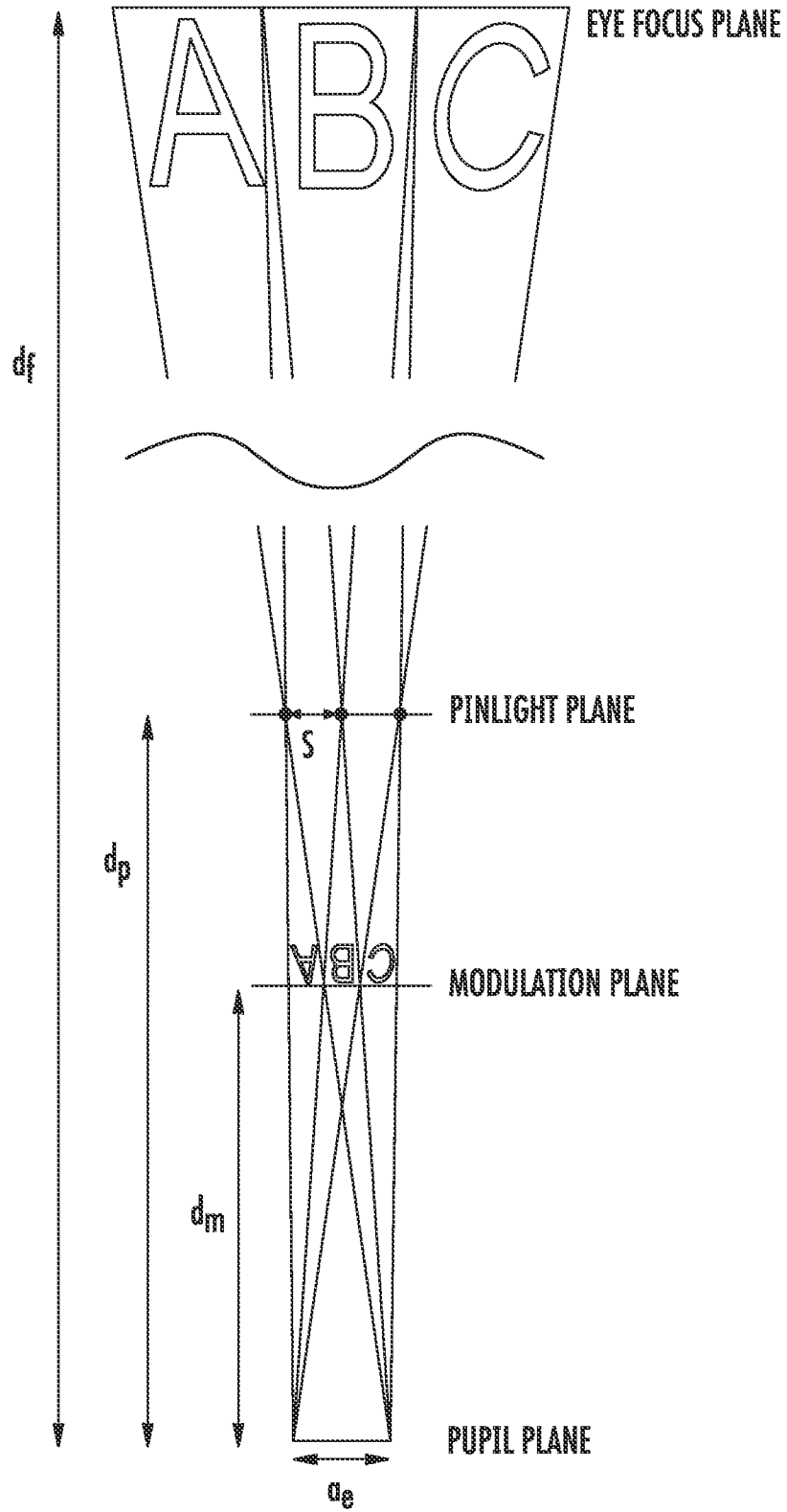


FIG. 3

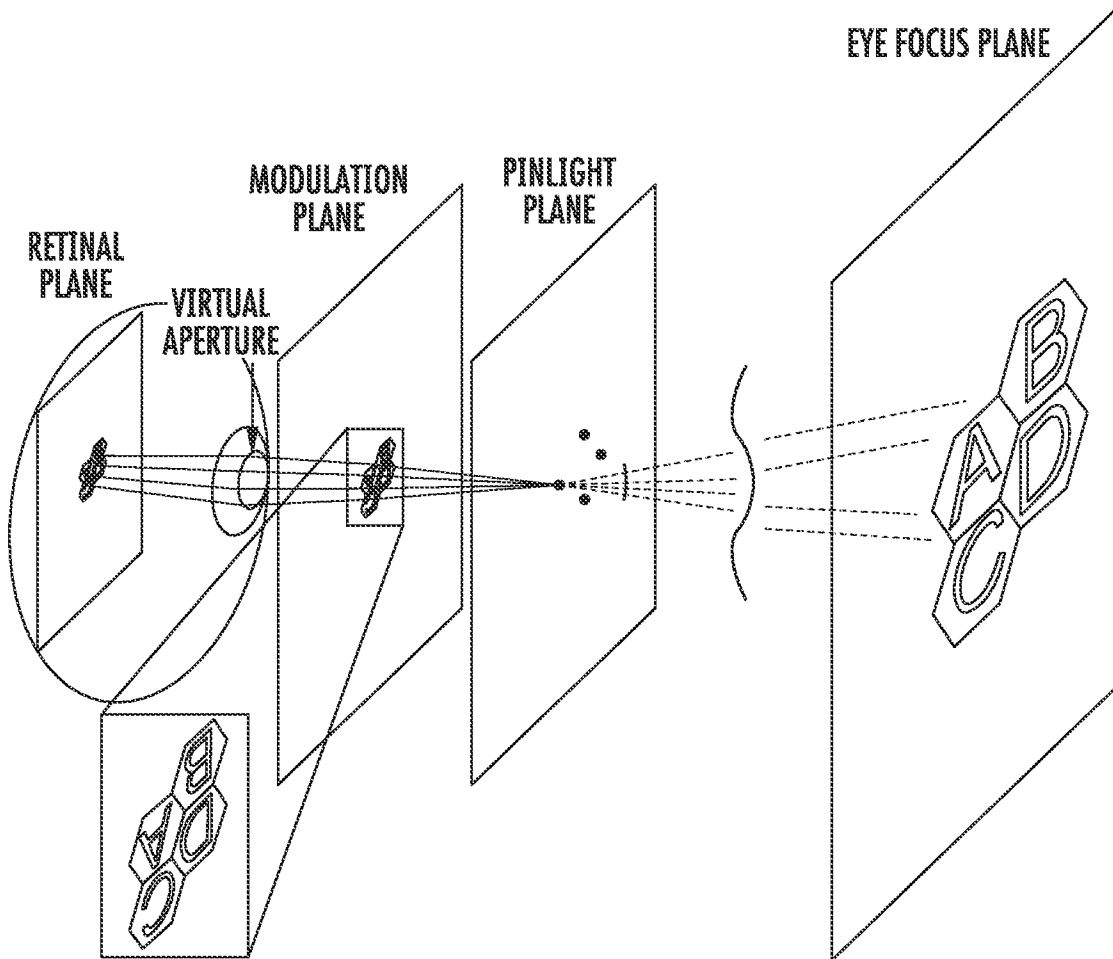


FIG. 4

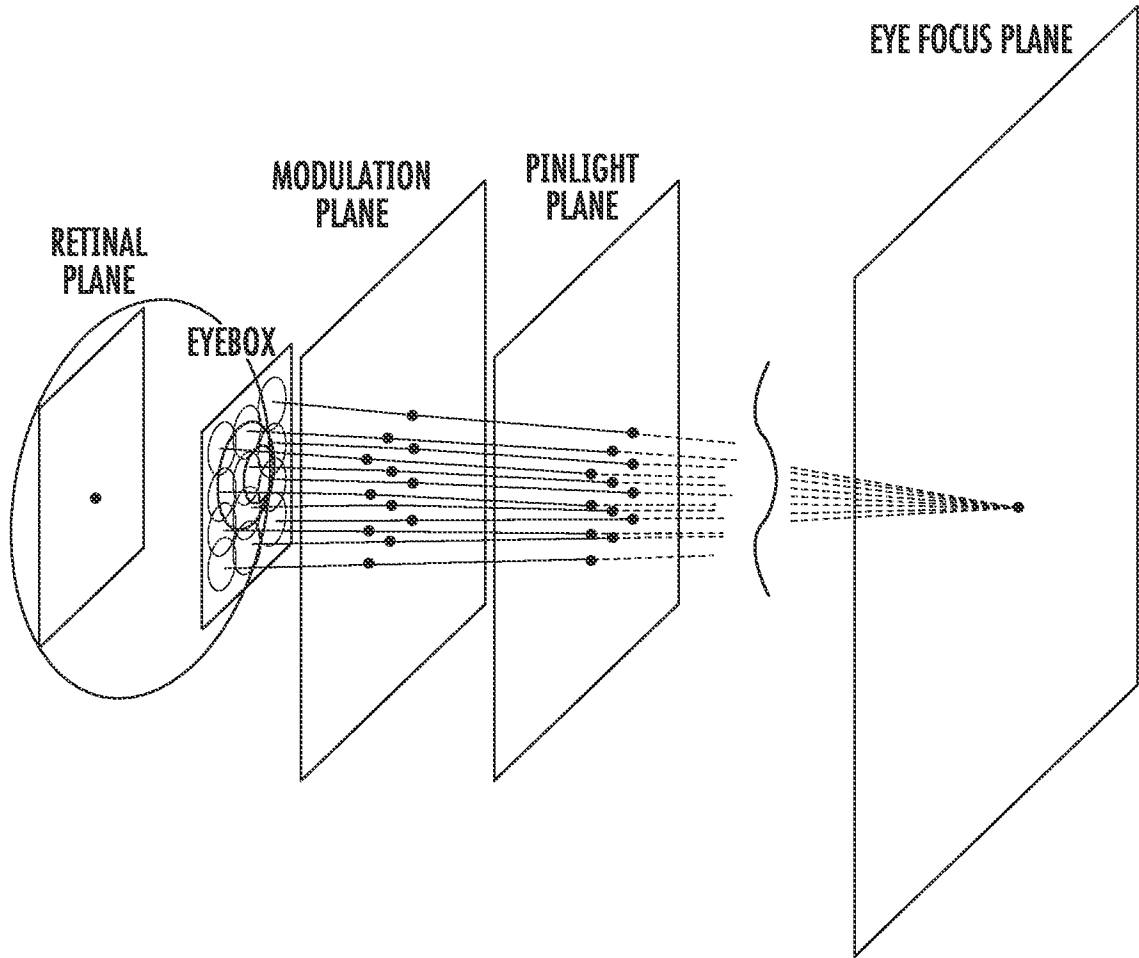


FIG. 5

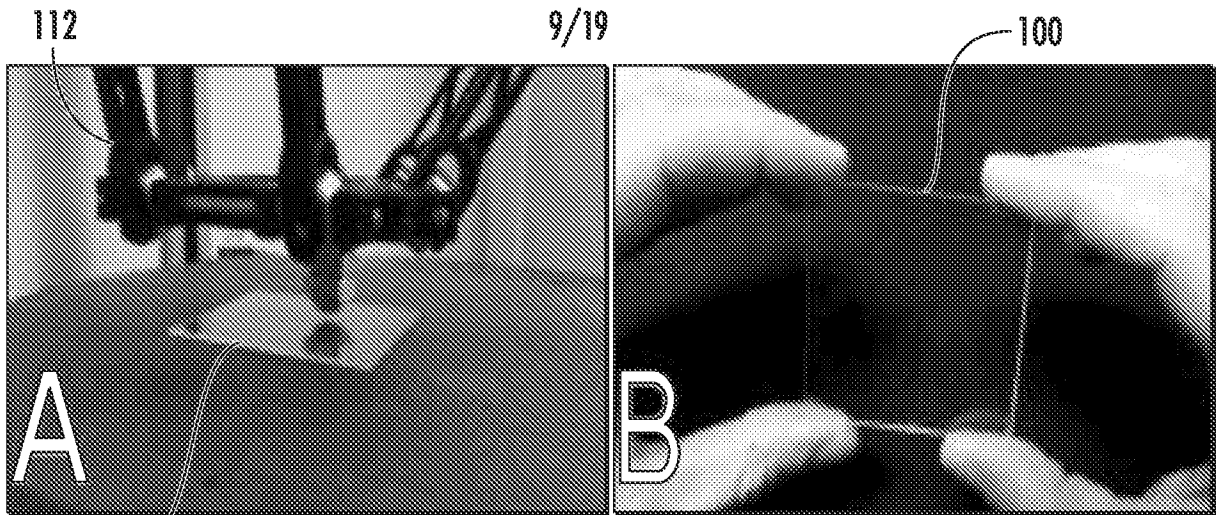


FIG. 6A

FIG. 6B

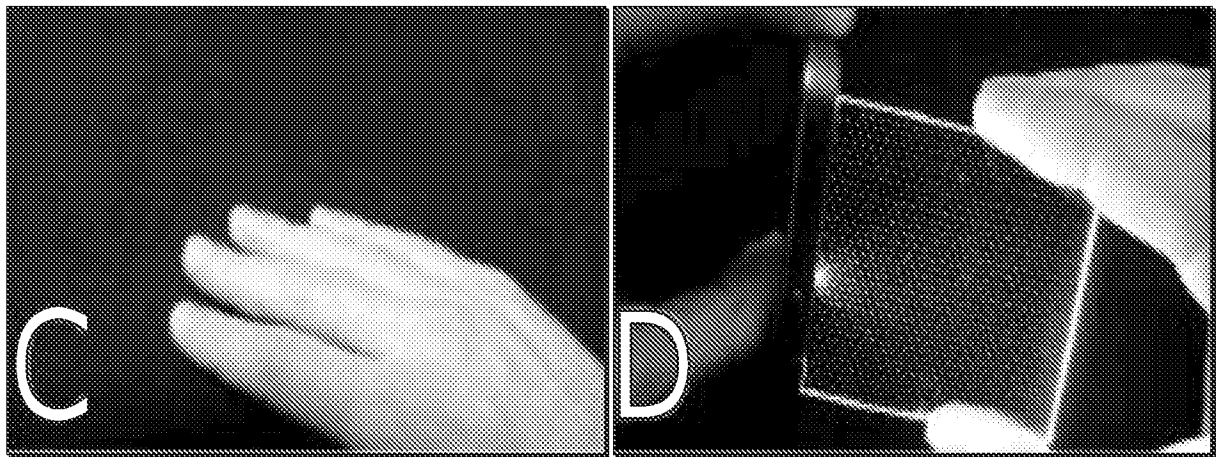


FIG. 6C

FIG. 6D

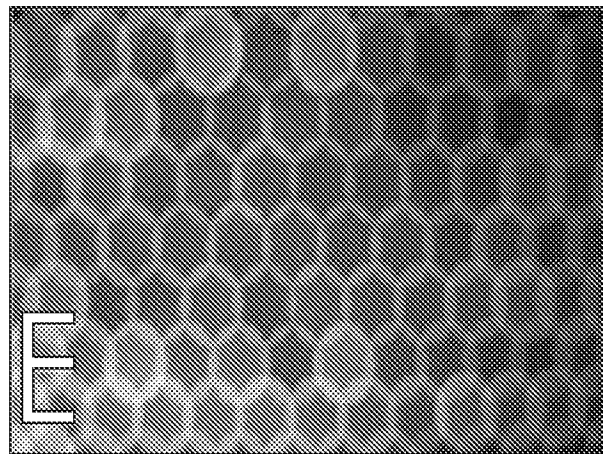


FIG. 6E

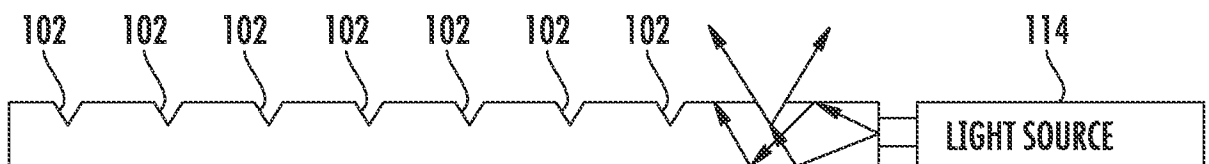


FIG. 6F

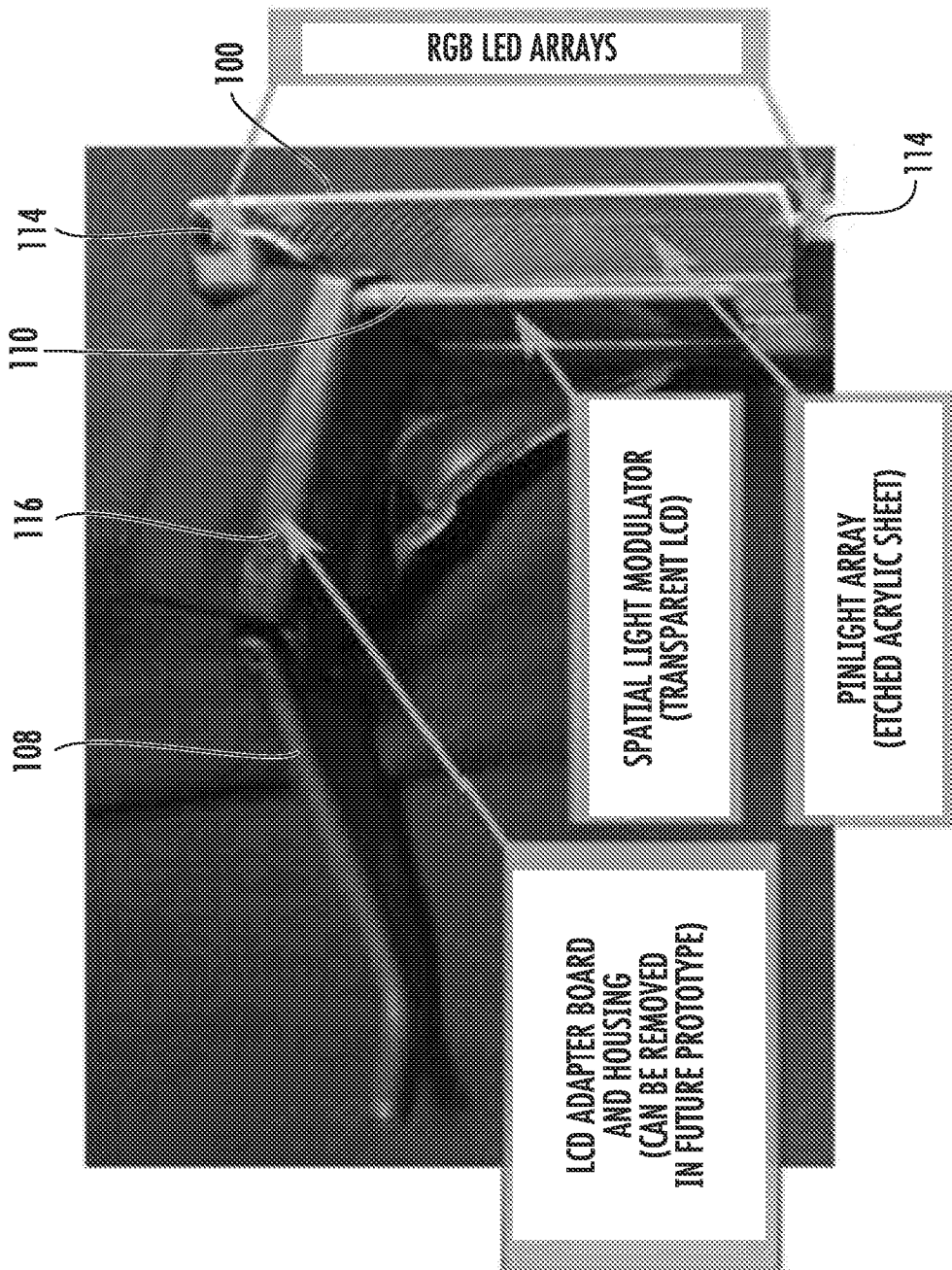


FIG. 7

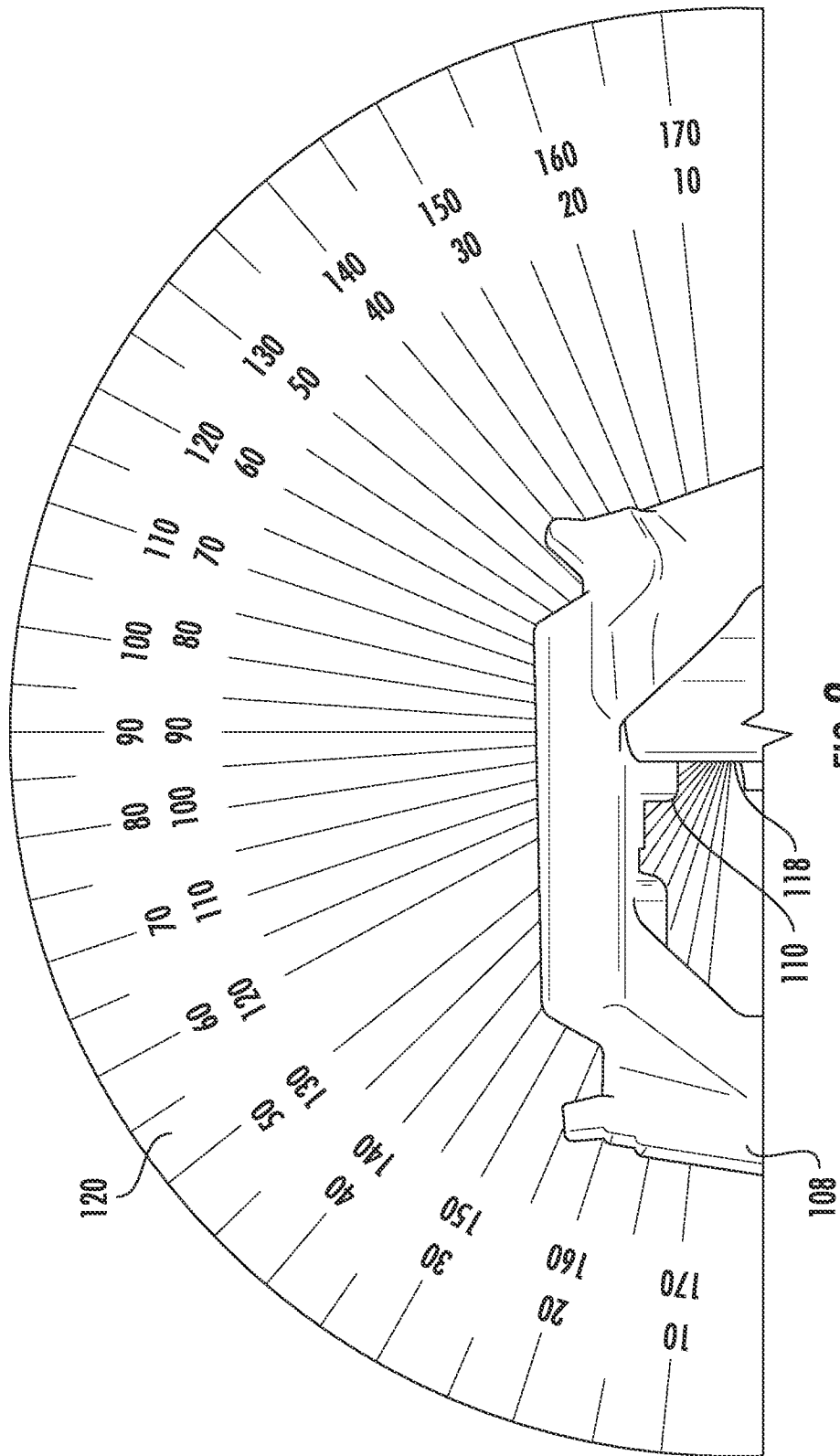




FIG. 9

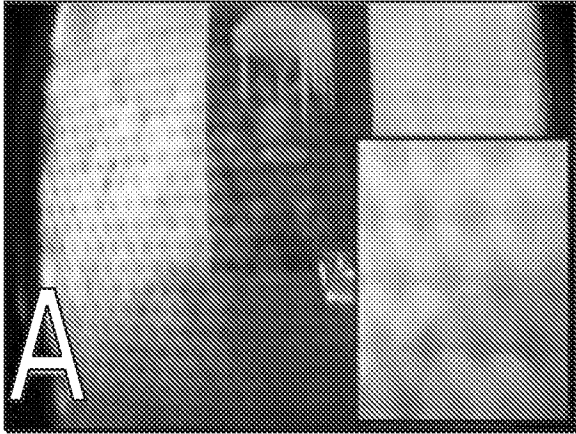


FIG. 10A

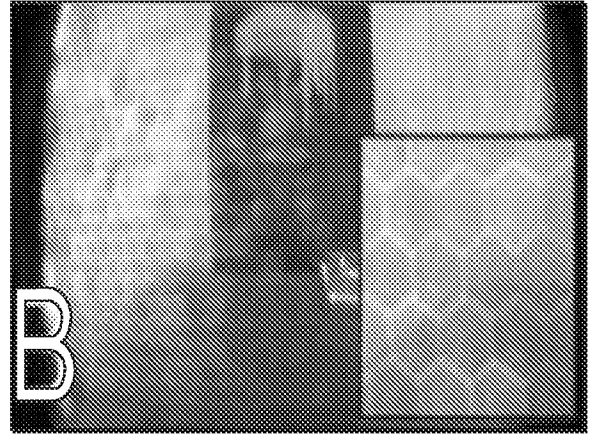


FIG. 10B

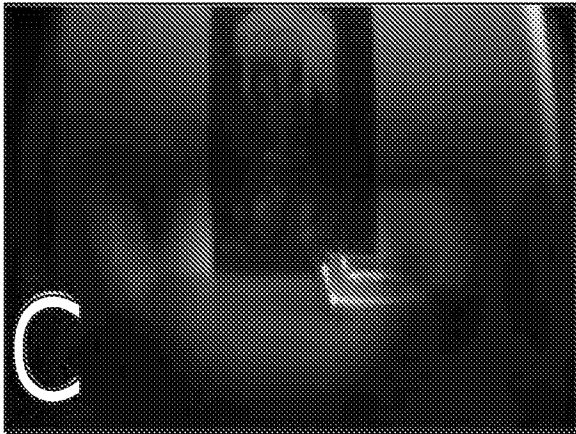


FIG. 10C

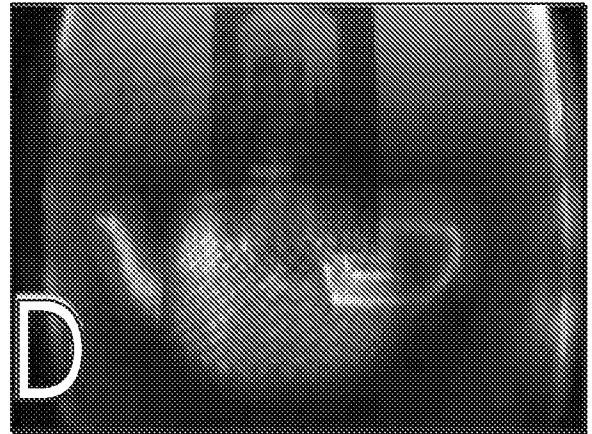


FIG. 10D



FIG. 10E

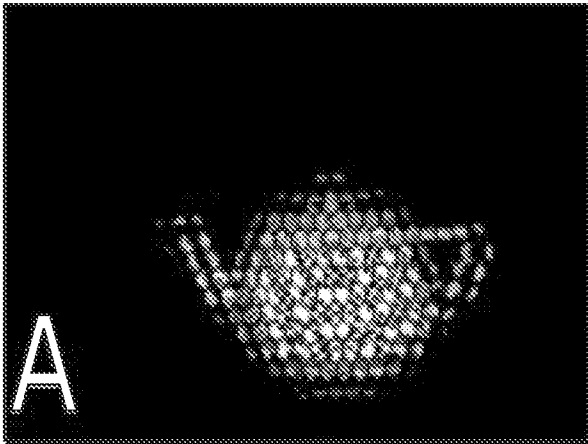


FIG. 11A



FIG. 11B

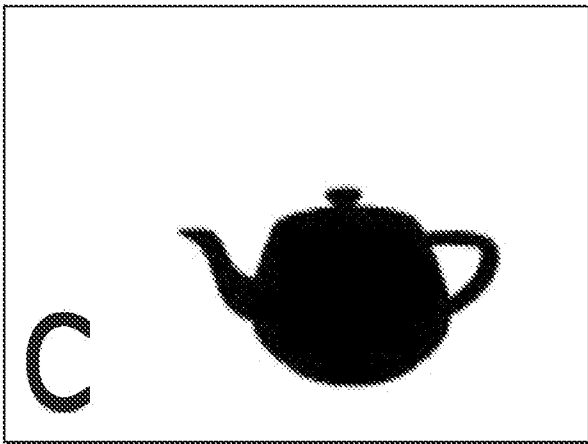


FIG. 11C

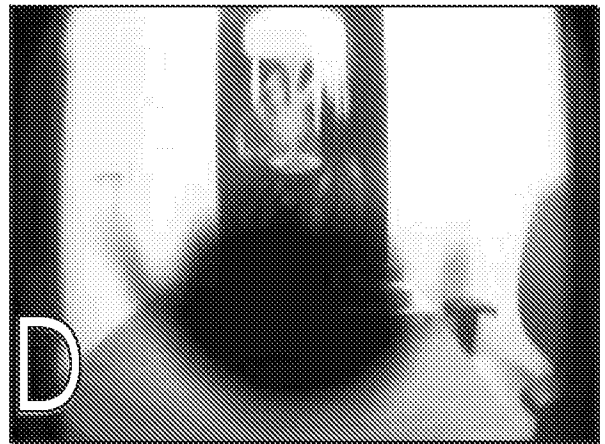


FIG. 11D

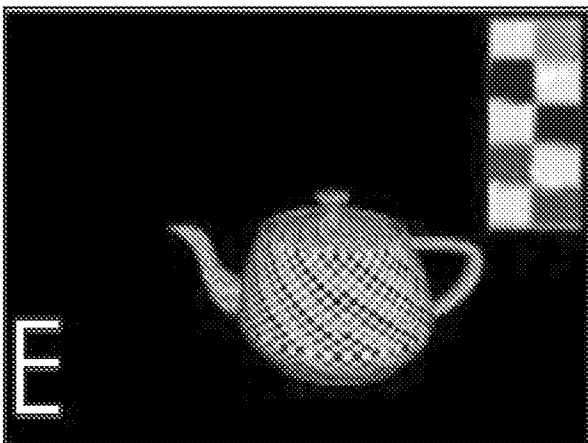


FIG. 11E



FIG. 11F



FIG. 12A

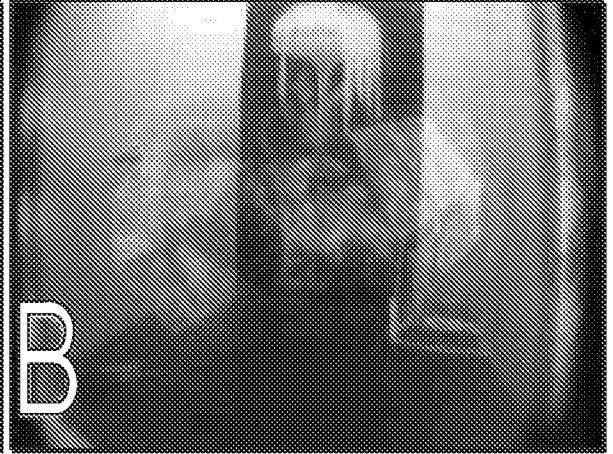


FIG. 12B

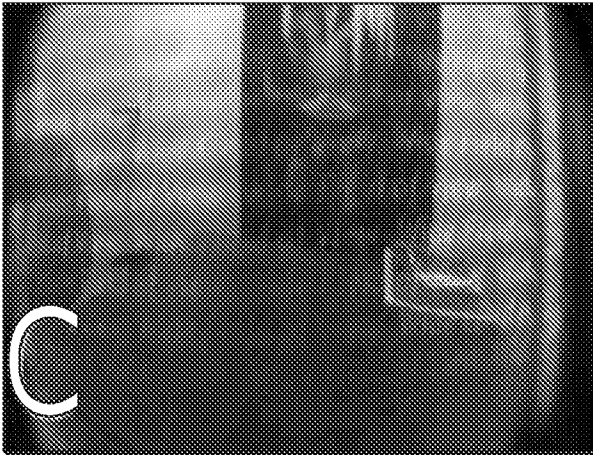


FIG. 12C

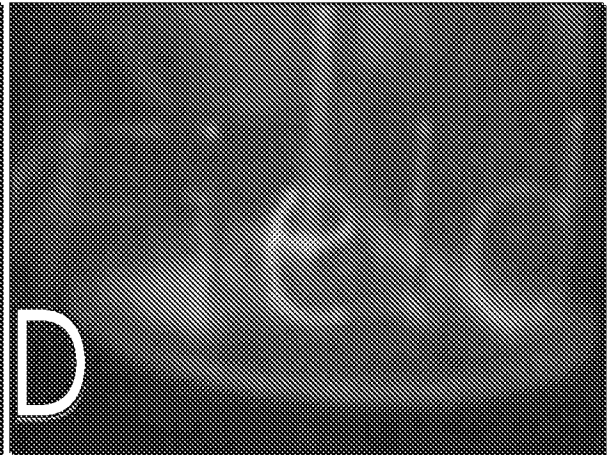


FIG. 12D

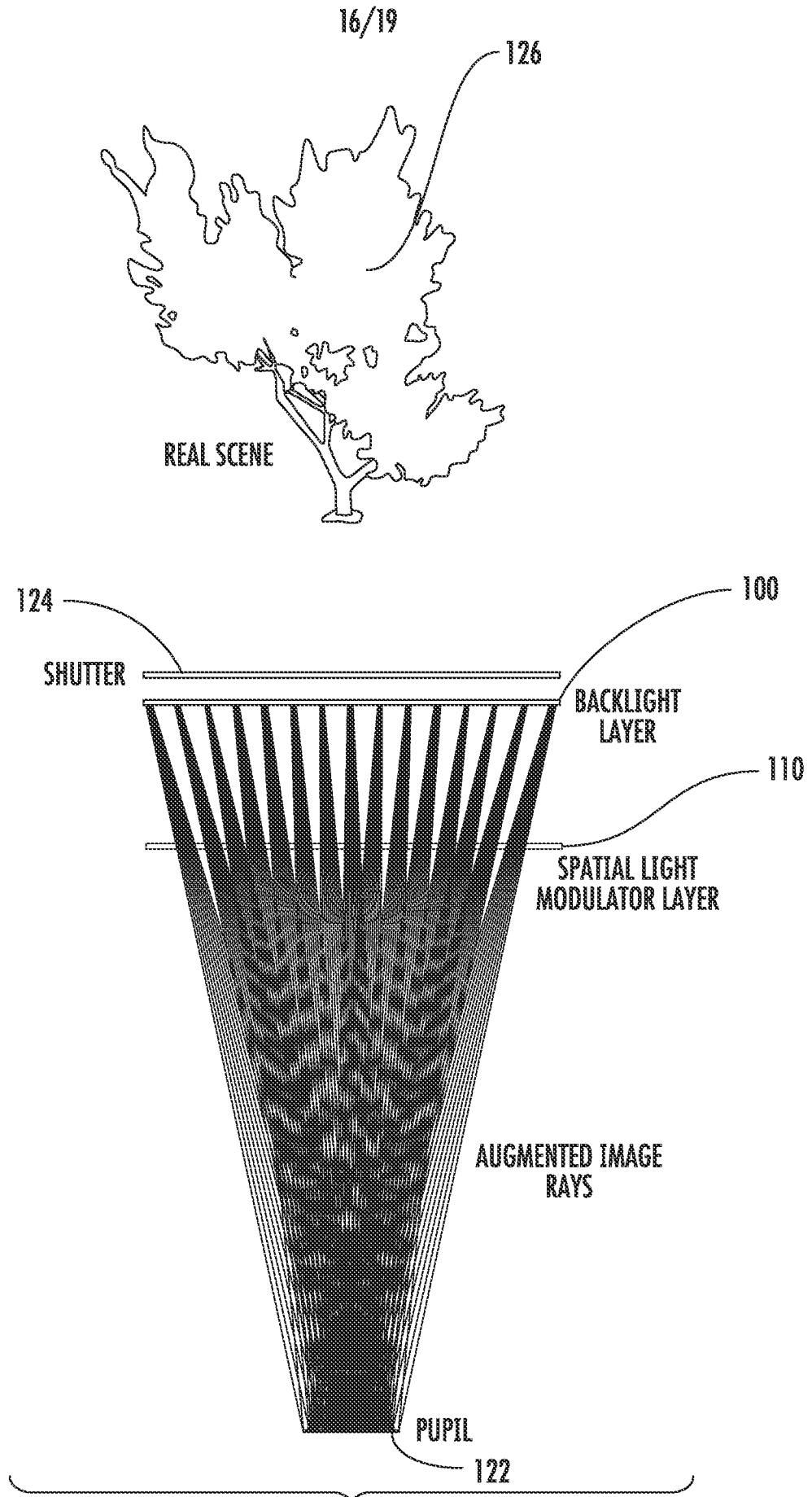


FIG. 13

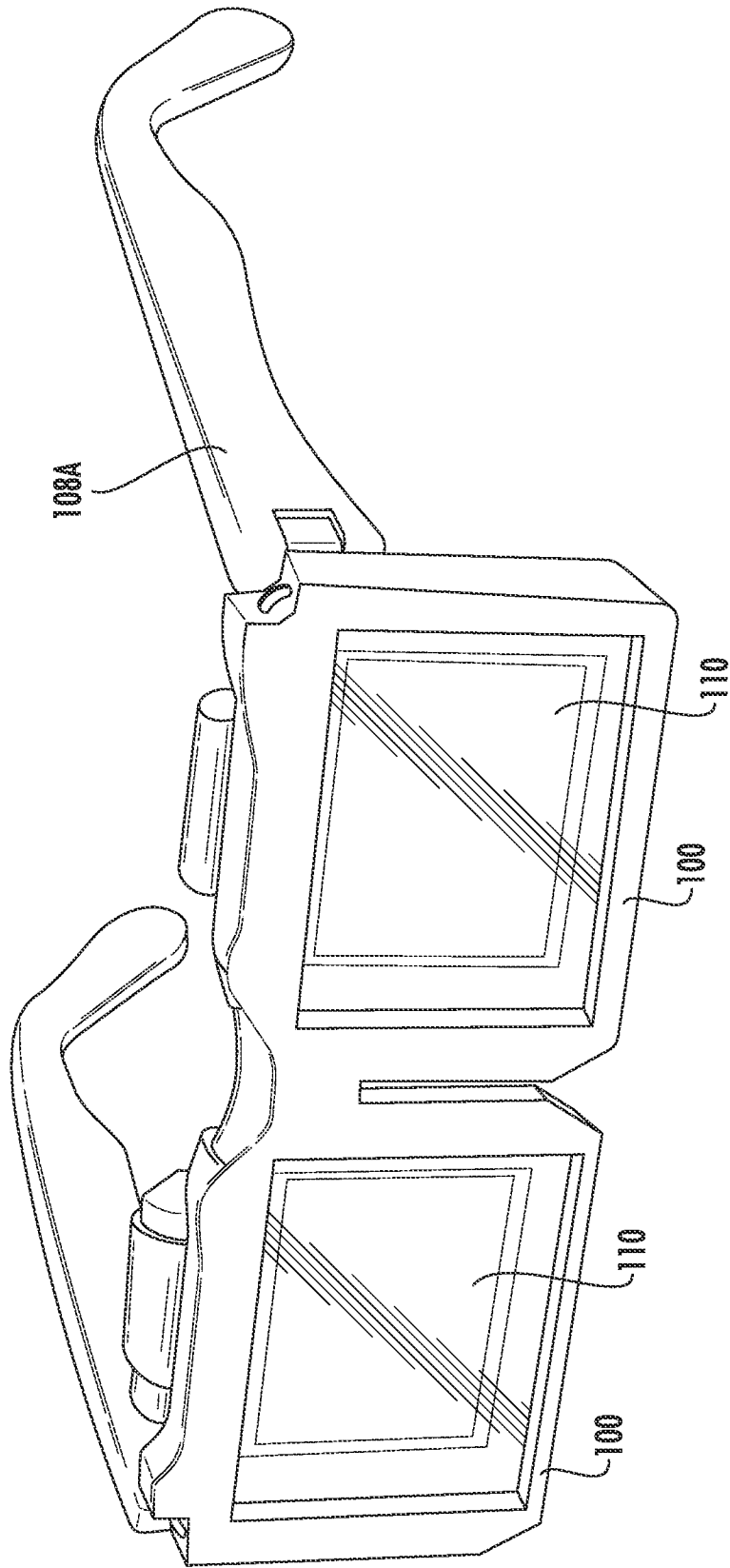


FIG. 14

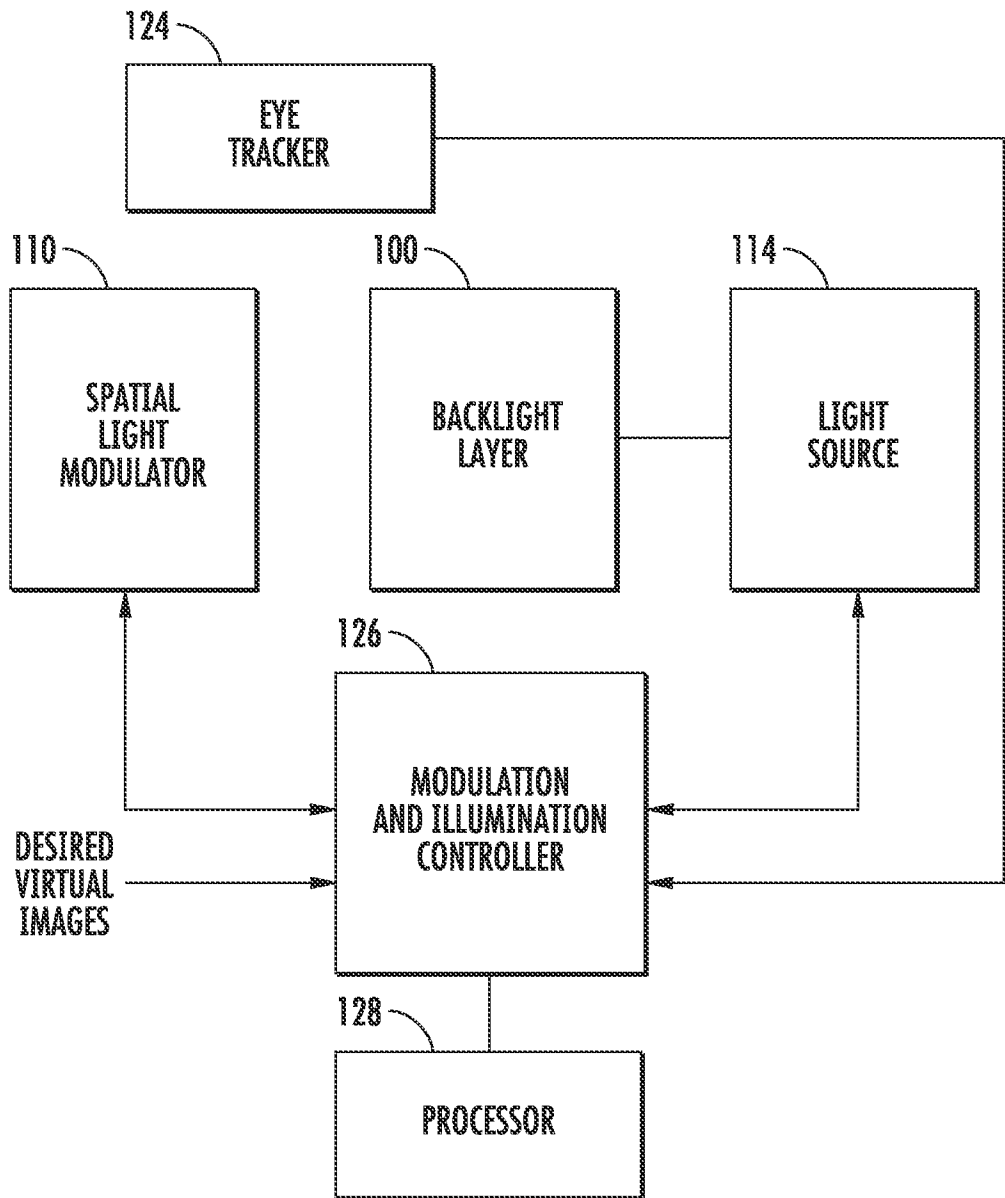


FIG. 15

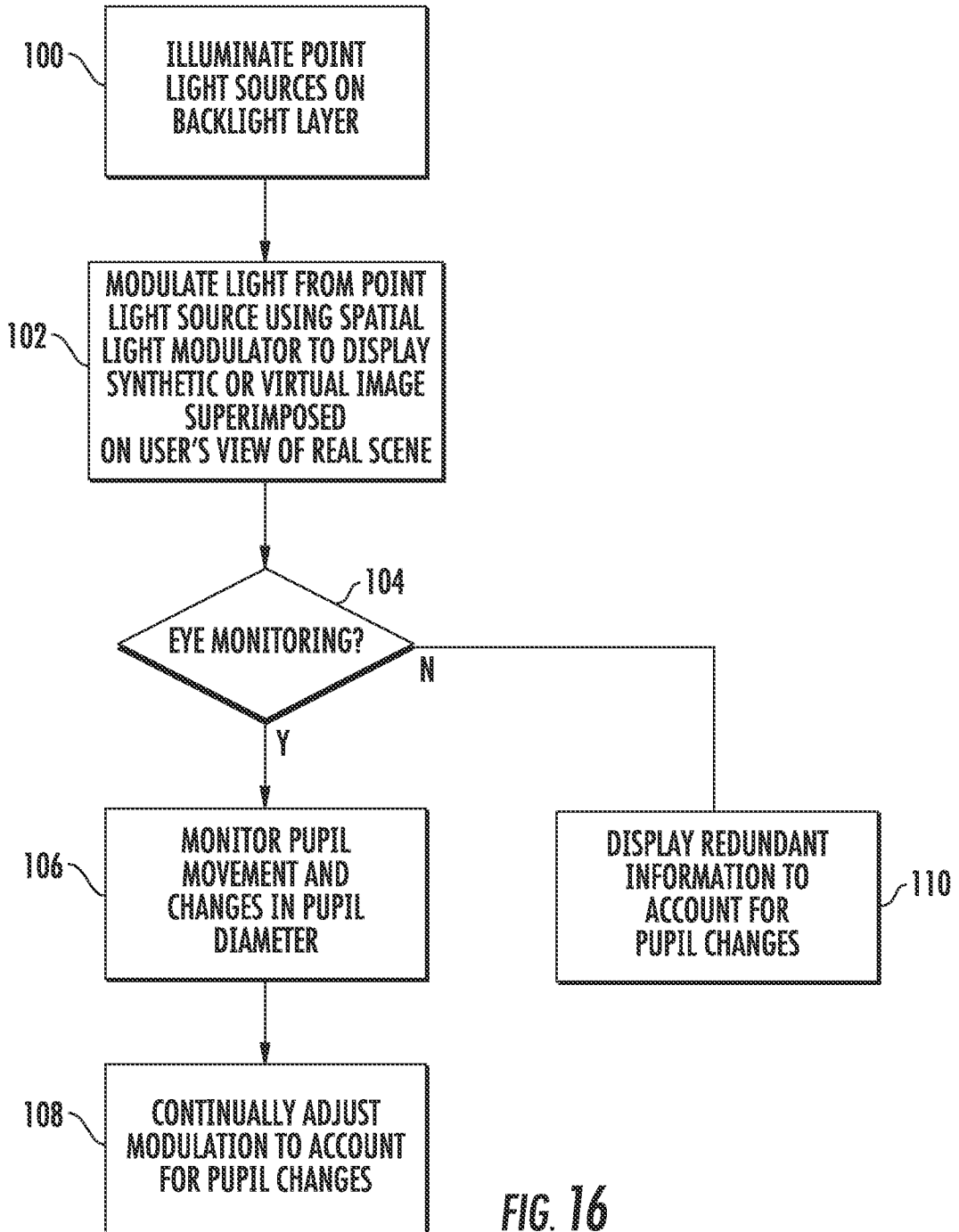


FIG. 16