

International Patent Application of
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For
Immersive Optical Projection System

Cross-Reference to Related Applications

This international patent application claims the benefit of US provisional patent application Ser. No. 62/399,530, filed on the 26th of September, 2016 and US non-provisional patent application Ser. No. 15/716,503, filed on the 26th of September, 2017 by the present inventor.

Technical Field

The present disclosure relates to a virtual reality system that in one case, provides a photoreceptor density limiting, wide angle, full spectrum, binocular vision, real optical depth of field, imaging system in a head mounted form factor.

Background Art

Many devices have been created to deliver optical information to the human eye. Visual information can take the form of high definition video, computer generated content, two and three dimensional content, text, etc. The visual component of a virtual reality system delivers synthetic content directly to the eye, whereas augmented reality systems blend generated content with a real world views.

In nature, every illuminated particle reflects or emits rays of light in every direction and in a multitude of wavelengths. The rays that reach us from afar are nearly parallel and those that arrive from a nearby point are more divergent. The arriving beams that pass through our pupils are focused, or made more convergent, as they pass through the cornea, the aqueous humor, the crystalline lens, the vitreous humor and finally, the retina.

For normal vision, an image will be formed on a portion of the retina that is dependent on the entrance angle of the beam with respect to the optical axis of the eye, or direction of gaze. Those images that form in the central 2 degrees of vision fall on an area of the retina with an exceptionally high density of photoreceptor cells called the fovea. It is here that most of the high resolution visual information is converted from optical to electrical nerve impulses via the photoreceptors, and transmitted to the visual cortex via the optic nerve bundle. Photoreceptors further away from the fovea detect off axis images and contribute to the sense of peripheral vision. In total, there are approximately 15 million rod cell and cone cell photoreceptors. Rod cells detect low levels of light, but no color, and cone cells detect color, but only at higher levels of light intensity. Three types of cone cells sensitive to red green and blue light, are predominantly found in the high density central area of the retina, thereby providing high resolution color vision.

Because central vision contains so much more information, the eye will rapidly “scan” or saccade on one important target, say a face or moving object, and jump to another at a rate of up to 1000 Hz. The eye will also “jitter” or micro saccade to provide continuous sensitization to the retina. The eye can rotate up/down

and left/right about a central point at a speed of up to 900 degrees per minute. Although the eye can rotate in excess of 50 degrees in various directions, depending upon age, individuals rarely exhibit eye motions exceeding plus or minus 10 degrees from a straight ahead gaze.

An eye, with a fixed forward gaze, can detect light impinging on the cornea from an angle of nearly 110 degrees towards the temple, and about 59 degrees towards the nose. The field of vision also extends to approximately 56 degrees above and 70 degrees below the direction of gaze.

In addition there is the coordinated movement of the eyes with each other to provide for binocular vision and depth perception. There is coordinated movement of the eyes with respect to head position to maintain fixed targeting of a stationary object during body motion or stable targeting of a moving object. The crystalline lens can also deform via the ciliary process to increase its focusing power and bring a near object whose rays are more divergent, to a sharp focus on the retina.

A typical movie projector produces a focused image on a curved or flat screen at a distance. A curved screen helps to improve the sense of immersion with a modest increase in peripheral vision. In both cases, the distant screen provides reflected parallel light beams that can easily be focused by the human eye, but lends little parallax or binocular information.

Viewing a distant screen with "3D" glasses can provide a sense of depth. These devices utilize various techniques to deliver a slightly different view angle to each eye. Most are limited by frame rate, brightness, and the production of a truly divergent ray field that a near object would produce. And of course, they are all subject to the flat field, limited resolution, limited dynamic range and limited angular extent of the distant screen. An improvement in field of view occurs when moving a screen closer while using 3D glasses. Although closer, the depth of focus remains constant and relaxed distant focus is lost. The field of view is also only a small subset of the visual potential.

Additional information content can be added by a "heads up" display whereby information is projected on the surface of a visor or screen. Using a combination of scanners and optical elements, a virtual image can be produced at any depth, but is usually limited in scope. Such information may overlay the true visual field. The overlay of a computer generated, or other video source on a true direct view of a scene falls in the realm of augmented reality.

Finally, virtual reality goggles, or machine augmented reality attempts to provide all the visual clues, including opposing head/eye motions, and binocular vision, to give a sense of total immersion. Most provide a modestly wide field of binocular view, but are limited in delivering true divergent fields that would be produced by near objects. They are also limited by the inability to accurately synchronize head motions with the simulated visual field. They also suffer from sensory conflicts between the human vestibular system and the projected visual field, resulting in motion sickness. And without the knowledge of where the direction of gaze is located, the total information bandwidth must be spread evenly over the field of vision, thereby wasting it on low acuity peripheral vision.

Summary of Invention

What is needed then is a visual, total immersion device that can provide optical stimulation to each of the 15 million rod and cone cells of the retina in a way that accurately simulates depth perception, a binocular parallax, a large color space, a maximum field of view, and does not compromise the motion sensory functions of the vestibular system. And from a standpoint of practicality, it must be relatively inexpensive to manufacture, robust, and may have the ability to selectively deliver maximum resolution and bandwidth to the central field of view.

Brief Description of Drawings

Figure 1 - Monolithically Micromachined Beam Steering Device

Figure 2 – Divergent Micro Lens

Figure 3 - Two Degree of Freedom Optical Scanner with Divergent Micro Lens

Figures 4, 5, 6 – Variable Focus Optical Element

Figure 7 – Quad Array of Optical Scanners

Figures 8 and 9 – Wide Angle Scanning Array Projector

Figure 10 – Reflector Scanner Imaging System

Figure 11 – Eye Tracker

Figure 12 – Reflector Scanner Imaging System with Sealed Optics

Figure 13 – Isometric 3D View of the Reflector Scanner Imaging System

Figure 14 – Imaging of Near Objects and Accommodation

Figure 15 – Creating Real Images Exhibiting a True Depth of Field from Virtual Objects

Figure 16 – Single DOF V-Gap Optical Element

Figure 17 – Close-up detail of V-Gap Optical Element Hinge Area

Figure 18 – Small Cross Section of Adaptive Optics Reflector Array

Figure 19 – Fixed Array of Variable Focus Optical Elements

Figure 20 – Steerable Variable Focus Optical Element in a Convex State

Figure 21 - Steerable Variable Focus Optical Element in a Concave State

Figure 22 – Array of Steerable Variable Focus Optical Elements in a Concave State

Figure 23 - Array of Steerable Flat State Optical Elements

Figure 24 – Metamaterial Beam Steering Plates

Figure 25 - Metamaterial Beam Steering Plate Array

Figure 26 – Array of Micro Scanner Direct Projection Optical Elements

Figure 27 – System Integrating Glasses

Description of Embodiments

Figure 1 shows a monolithically micromachined beam steering device, **102**. Its design and function is the subject of patents US 5,872,880, US 6,086,776, US 6,127,926, and US 7,201,824 B2. Light is first introduced, from a remote light source, into the core of optical element **116** at point **118** and is emitted from the core at point **120**. In one embodiment, the slightly divergent beam travels a short distance through free space and strikes the surface of double gimbaled micromirror **108**. In another embodiment, an optical element such as a ball lens, a GRIN lens, or any other optical element may be

introduced after point **120** to modify beam characteristics further on its way to double gimbaled micromirror assembly **106**, including dynamically controlling beam divergence with a variable focus lens. Once the beam strikes micromirror **108**, it can be controllably directed away from the substrate surface with two degrees of freedom.

The first and second nested gimbal frames of double gimbaled micromirror assembly **106** can move independently, and in one embodiment, are driven with electrostatic forces between pads on each respective gimbal frame and substrate wall **110**. In this example, an electrical control signal is introduced on pads **112**, producing charge flow through address lines **104** resulting in a charge profile on the electrostatic actuator pads. The extent of gimbaled rotations in the up/down and left to right directions is a function of clearance between micromirror assembly **106** and lower v-groove cavity **110**, thereby defining the boundaries of beam deflection in the up/down, left/right directions. It can be appreciated that the angular motions and positions of micromirror **108** can be very precisely controlled by the manipulation of current, magnetism, charge, voltage potential, thermal expansion, shape memory effect, or any other presentation of force.

Precision v-grooves **114** and **110** are anisotropically etched into the silicon substrate along the $\langle 111 \rangle$ atomic planes. Micromirror assembly **106** and its flexures are fabricated by standard MEMS processes before being released by the anisotropic etch. The resulting v-groove structures provide for highly accurate alignment of the optical axis of element **116** with the center of micromirror **108**. It can be appreciated that optical element **116** could take many useful forms including a small laser, or perhaps a laser and GRIN lens combination. It may also be appreciated that a double gimbaled laser could also take the place of the micromirror and directly produce a multi degree of freedom steerable beam.

Figure 2 shows a high Numerical Aperture (NA) negative lens **151**. The lower surface **150**, exhibits a hollowed out section **153**, although it could take any shape, and an upper surface that may be of any shape, including concave, convex, or flat and may be constructed from any optical material exhibiting refraction, reflection, metamaterial properties, birefringence, total internal reflection, etc. In this particular example, one possible function of negative lens **151** is to increase the total compound scan angles produced by micromirror **108**. It can be appreciated that additional optics may be placed after lens **151** if a resulting beam profile passing through lens **151** requires further modification. In one embodiment, registration edges **152** are etched into lens **151**'s upper surface to provide accurate assembly alignment for additional optics such as miniature prism **350**.

In one possible embodiment, Figure 3 shows the beam steering device **102** of Figure 1 mated with lens **151** of Figure 2. If lens **151** exhibits a net negative diopter, then it will produce an increase in an emerging beam's scan angle with two degrees of freedom. In general, lens **151** may take the form of a doublet, singlet, compound, lenslet array, positive, negative, an achromat, asphere, GRIN, reflective or refractive, multi-dielectric stack, prism, emitter, absorber, light sensor, temperature sensor, magnetic sensor, magnetic coil, photodiode, or any other optical configuration. Lens **151** could also be focusable in that one or more of its optical components could be controllably moved in a direction normal to, or in a direction lateral to a surface of beam steering device **102**. Further, relative motions between elements of lens **151** could be controllably provided with piezoelectric stacks, acoustic forces, magnetic forces, electrostatic forces, thermal forces, or any other application of force that is known to those in the art.

Figures 4, 5, and 6 show the cross-section of a Variable Focus Optical Element **615**, that has the capability to provide variable focusing power to beams of light impinging on its surface. This can be useful for reforming a divergent beam that strikes concave reflective surface **262** for example, as shown in Figure 6, or simply reflecting the beam off flat surface **261** in the case of Figure 5, or scattering an impinging beam in the case of convex surface **260** as shown in Figure 4. In Figure 4, negative charges **270** and **272** are injected onto the conductive surfaces **250** and **260**, thereby providing a repulsive force that causes the thin film diaphragm **260** to bulge outward. Similarly, in Figure 6, opposite charges **252** and **254** are placed on the conductive surfaces **262** and **250** respectively. The resulting attractive forces cause reflective surface **262** to

assume a concave shape. If no charges are present, then the reflective thin film surface **261** remains flat, as in Figure 5. For a single mode beam on the order of 10 microns in diameter, this small, SDOF VFOE can respond very quickly to input commands. Insulator **258** can be formed on substrate **256** using standard micromachining techniques. Etching a hollow cavity beneath the optical surface may be accomplished by providing a series of perforations about its circumference. Alternatively, the cavity could be produced prior to wafer bonding with the optical components of the upper surface. There are many equivalent ways in which this device can be fabricated. If conductive, the optical surface might also provide for actuation forces as well. The optical surface of a VFOE **615**, can take the form of a simple micromirror, a multilayer dielectric stack, a metamaterial, an optical grating array, a static convex or concave optical element, an actively variable concave or convex optical element, or any other optical element that can transmit, absorb, polarize, upconvert, downconvert, lase, emit, refract or reflect electromagnetic radiation.

It must also be noted that the method of action should not be limited to electrostatic forces only. For example, micro-coils formed on surfaces **260**, **261**, or **262** and lower conductor **250** can produce magnetic forces sufficient for deflection, or a magnetic material could be utilized on a surface facing a micro-coil to provide these forces. Gas or liquid pressure within the cavity could also provide a deformation force. These pressures could be provided by a high or low pressure source, or could be produced by a hot or cold sink imparting work on the fluid. Similarly, thermal bimorph, shape memory effects and phase transformation of some solids such as wax could also provide these desired deflection forces. In fact, any force implementation to produce controllable deflections of the reflecting surfaces may be used.

In one embodiment shown in figure 7, quad array **370**, is defined by a grouping of four micromachined beam steering devices **102**, that are provided with negative lens elements **151**. Optical elements **300**, **302**, **304** deliver the single frequency colors of red green and blue to the steering micromirrors, **108**. The fourth optical element, **306**, can be used to expand the color gamut with an additional color such as yellow, or may be used as a scanning sensor to detect incoming light signals to determine, in one example, the reflected position of the pupil with respect to the head. As before, pads **112** deliver voltage control to independently steer each of the four micromirrors **108**. Of course any frequency or combination of frequencies can also be delivered through any one of these optical elements.

Figures 8 and 9 show one possible combination of a multitude of sub-projectors, **371**. The grouping, taken as a whole, will be referred to as a Wide Angle Scanning Array Projector or WASAP. As a two degree of freedom beam emerges from quad array optical scanner, **370**, it is projected up and away from its upper surface, then deflected in the horizontal direction by right angle turning prism, **350**. As described previously, the miniature prism, **350**, is bonded to the surface of the quad array, **370**, and is precisely aligned over the emerging beams with the help of registration grooves **152**. This creates a sub-projector, **371**. Then eight of these sub-projectors are placed on a common substrate, **352**, and fixed at predetermined relative angles with a high degree of precision. Three sub-projectors, **371** facing to the rear, cover approximately 180 degrees of scan angle on the upper surface of substrate **352** as exemplified by vectors **354**, **356**, and **358**, wherein each sub-projector **371** provides for 60 degrees of scan angle in this one particular embodiment. A single sub-projector **371** on the upper surface faces forward as shown by vector **364**. An identical symmetric configuration is provided with four more sub-projectors **371** on the lower surface of **352**, thereby providing an additional scan space defined by vectors **366**, **368**, and **372**. In this particular example, approximately 180 degrees of horizontal scan and 120 degrees of total vertical scan are provided. The forward facing sub-projectors **371** directly project into the eye so as to “hide” the WASAP from a direct gaze forward. Of course, if the WASAP is located out of the field of view, then forward projecting sub-projectors **371** would not be needed. It can be appreciated that Figures 8 and 9 show one possible combination of a multitude of quad array optical scanners **370**. Further, it can be appreciated that in its simplest form, a single beam steering device **102** affixed to a headset in close proximity to the eye could provide a full immersion, wide angle view.

Figure 10 shows the general layout of a reflector scanner imaging system and its interrelation of components that projects a wide angle, full color gamut, high resolution image directly to the eye. This view is a horizontal cross-section of the imaging system. The ray traces are equally valid for any other plane whose normal vector is orthogonal to the optical axis of the projector's field, or the eyes' axis. A scanning projector **440**, is placed near the center of an approximately conic reflector, **442**. A compound curved, first surface mirror, **422**, provides a means for reflecting beams emanating from scanning projector **440**, back towards the pupil, and ultimately, the retina. The angular position of the pupil may be determined with a form of "eye tracker" using a pulse of IR light provided by one or more IR emitters **428**. It may be appreciated that other wavelengths of light may be used as well. An array of eye tracking sensors **436**, disposed on the inner surface of reflector **442**, detect reflected light from the user's pupil and/or cornea. This information can be used to deduce the exact position of the eye relative to the head. Eye tracking sensor **436** can also take the form of an inward looking camera. A camera can be used in the usual way to observe corneal reflection patterns, retina physiology, or the dark IR reflections emanating from the pupil to ascertain eye position. Another novel approach would require the "ink jet" assistance of placing one or more fluorescing dots directly on the user's cornea or sclera. Although invisible in normal light, a pulse of deep violet light would provide cameras or sensors with the exact registration position of the eye. Using two or more dots would provide for the determination of eyeball rotation as well.

The outer surface, **424** of reflector body **442** is shown with forward and lateral looking, wide angle cameras, **426**. These cameras would provide the exact field of view and binocular vision one would see if no display were present. By passing along this visual data and incorporating it into the VR data stream to each eye, the illusion of wearing no glasses at all would be complete. Of course these cameras might also detect other wavelengths of light including UV and IR. In addition, any other sensor could produce "synthetic vision" by providing magnetic, radio, acoustic, sonar, or radar data to name a few. Any radiation source that is detectable is viewable.

The shape of reflector **422** is approximated by ray tracing backwards from the retina to the scanning projector. The method is as follows.

A fundamental assumption is made here that a rod or cone cell's response to an impinging photon is invariant with respect to angle of impingement.

The following is a method for obtaining the surface form of a passive reflector that can transmit a highly collimated, focused beam to each and every rod and cone cell on the retina.

- 1) Obtain the family of vectors that is characterized by a ray trace originating from each and every rod and cone cell within a defined sector of the retina, wherein the ray proceeds through the center of the exit pupil and proceeds out from the cornea.
- 2) Arbitrarily select a projector point on the straight ahead gaze optical axis a given distance from the surface of the cornea.
- 3) Define a sphere of a given radius, centered on the point of projection selected in step 2.
- 4) Select a vector emanating from the center of the retinal sector analyzed in step 1.
- 5) Find the 3D point of intersection of vector 3, and the surface of sphere 3.
- 6) Calculate, if it exists, the normal vector for the differential reflector surface element that will satisfy equal angles of incidence and reflection.
- 7) Select another vector from set 1 and repeat steps 5 and 6.
- 8) Stitch together the correctly oriented surface elements found in steps 6 and 7. If the surfaces are not contiguous, then modify the initial projection radius until it is.
- 9) Repeat steps 7 and 8 until the full vector set in step 1 is exhausted.
- 10) If the resulting piecewise reflector surface is smooth and contiguous, repeat 1-9 to find all such sector surfaces and stitch together to form the finished reflector.

If the resulting surface cannot be made piecewise contiguous or smooth, then iterate to a solution in the following manner.

- 11) Increase or decrease the initial diameter of the projection sphere in step 3 and recalculate until a satisfactory surface is found, or
- 12) Move the point of projection closer or further from the cornea in step 2 and recalculate, or
- 13) Obtain a second, much larger set of vectors within the selected retinal sector that represent a ray emanating from a photoreceptor through any point within the exit pupil.
- 14) Select the smoothest surface previously found, and recalculate for the new set of photoreceptor vectors found in step 13.

If an acceptable reflector surface still cannot be found, then a corrector lens may be added.

Finally, if all else fails, then an adaptive optical or metamaterial reflector will satisfy the surface solution for all central exit pupil vectors.

A passive reflecting surface defined thusly, will provide for full access to every photoreceptor in the eye. However, if a distortion free, true near-field image behind the retina is difficult to create using a passive display alone, an adaptive reflective surface may be used instead.

So, once all visual or other data has been gathered and processed by high speed algorithms and transforms in such a way that addressing each photoreceptor with the correct intensity, color, timing, and relative position to provide the illusion of a true image projecting on the surface of the retina, then that information is passed to the scanning projector **440**.

Having a full scan field, the projector emits multiple simultaneous scans from each sub-projector, **371**, to each sector of the visual field it has been assigned to address. Each beam from the six rearward facing sub-projectors reflect off first surface reflector **422** and impinge on the cornea **420**. The light then passes through the aqueous humour **415**, past the iris, **410**, through the crystalline lens, **408**, through the vitreous humour **406**, and onto the surface of the retina, **402**. With eye tracking information, it is possible to increase the bandwidth of a sub-projector **371**, when the forward gaze of the eye is in the visual field assigned to it. This is advantageous because visual acuity is by far, the greatest at the center of the visual field, as determined by the fovea, **400**. And bandwidth, of course, is not unlimited, so smart allocation may be in order.

Prior art teaches many methods for determining the position of the pupil relative to the head. The most commonly used form of gaze sensor consists of a remote or head mounted source of IR light that is projected towards the eye and a remote or head mounted camera that can observe the pupil position or the resulting reflection patterns from the cornea.

Figure 11 shows one possible configuration for a high speed eye tracker, wherein the inner surface of reflector body **442**, is covered with an array of photodiodes, **436**. These photodiodes, **436**, are interstitially placed between beam reflectors **604**, or direct projection sub-elements, **820**. A short burst of IR radiation is sent to the eye via IR emitters **428**, or scanning projector **440**. The resulting return signal is projected onto the sensor array and the pupil's image is found by comparing the strength of the signal from those sensors that are in a "shadow" **602**, and those sensors that are in a bright area, as is sensor **600**. With a fine enough coverage, a good geometric image of the pupil radius, **608**, can be determined and the center of gaze can then be deduced. As photodiodes can respond very quickly to a signal, this would provide for a high speed eye tracker.

Figure 12 shows one way in which the immersive optical projection device might be sealed. The introduction of a refractive corrector plate, **450**, provides for both sealing the delicate first surface reflector, **422** and scanning projector **440**, as well as correcting for a user's astigmatism, or furthering the refinement

of the projected beams as they ply their way to the eye, **460**. The reflector body, **442**, may be hermetically sealed to the corrector plate, **450**, providing for a moisture resistant environment.

Figure 13 shows an isometric 3D view of the reflector scanner imaging system and the relative positions of the eye, **460**, the reflector body, **442**, the scanning projector, **440**, the first surface reflector, **422** and the outer surface of the reflector body **424**.

Figure 14 shows the optical paths of a near object and the resultant images produced on and behind the retina. A vertical cross-section of the optical paths involving a distant object **504**, and a near object **506**, with respect to eye **460** is shown. The retina, **402**, is represented by a circle and the crystalline lens and cornea are represented by a simple double convex lens, **408**, with a focal length found at point **520**. Using simple lens geometry, we select a horizontal beam of light, **501** emanating from the tip **500**, of distant object **504**, and traveling parallel to the optical axis **531** of the eye. The beam progresses to point **508**, and is refracted through lens **408**, passes through focal point **520**, and strikes retina **402** at point **524** forming the tip of real image **532**. A ray **507**, passing from **500** through the center of lens **408** remains unaltered and also reaches tip **524**. As expected, the real image **532** is inverted and focused on retina **402**.

A similar ray tracing process from the tip **502** of near object **506**, produces a real image **530** that comes to a focus behind the eye at image tip **528**. It can be seen that beams **503** and **505** emanating from near tip **502** pass through the edge **508** and center **510** respectively of lens **408**, and impinge on retina **402** at points **524** and **526** respectively. Because they do not come to a focus on the retina, near object **506** appears blurred. If lens **408** attempts to accommodate to the blurred image, it will thicken, thereby increasing its optical power, and move near image **530** into sharp focus on retina **402**.

Figure 15 shows how an adaptive reflector array **575** can produce a real image exhibiting a true depth of field by selectively steering beams from a projected virtual object. In Figure 15, distant virtual object **556** and near virtual object **558** replace the real objects **504** and **506** respectively, found in Figure 14. In addition, an adaptive reflector array **575** is placed in close proximity to the viewer's eye **460**. The adaptive reflector array has the property that a multitude of steerable optical elements covering the surface closest to the eye can be individually adjusted at will to modify the trajectory of an impinging beam of light. This can be useful for emulating the divergent ray properties produced by a nearby object, as well as the nearly parallel ray emanations from a distant object.

Beginning at the tip **550** of distant virtual object **556**, a horizontal virtual beam **552**, parallel to optical axis **531**, proceeds to point **508**, and is refracted through lens **408**, passes through focal point **520**, and terminates at point **524** on retina **402**. And virtual beam **557** departs from point **550**, passes through the center **510** of lens **408**, and likewise terminates at point **524** on the retina. Of course a real image is not formed since virtual objects do not produce photons. However, by precisely defining the theoretical direction, color, and intensity of a virtual beam at the exact point of intersection with adaptive reflector array **575**, and substituting, at each point on the surface of that reflector array, a real beam of light exhibiting those exact properties, then a real image **530** of the virtual object **556** will be formed.

To create a real image of distant virtual object **556**, a real beam **568**, having the correct properties of direction, intensity and color calculated for virtual object **556** at that point, is emitted by projector **440** towards adaptive steerable optical element **560**. The steerable optical element **560** is tilted slightly out of plane with respect to reflector array **575** insuring that beam **568** is directed towards point **524**. Similarly, a correctly calculated beam **569** is emitted from projector **440** and strikes tilted steerable optical element **566** and proceeds to point **508**, and onto retina **402** at point **524**.

To create a real image of near virtual object **558**, a real beam **567** having the correct properties of direction, intensity and color calculated for the virtual object at that point, is emitted by projector **440** towards adaptive steerable optical element **565**. The steerable optical element **565** is tilted slightly out of plane with respect to reflector array **575** such that beam **567** is directed towards focus point **528**. Similarly, a correctly calculated

beam **569** is emitted from projector **440** and strikes tilted steerable optical element **566** and proceeds to point **508**, then point **520** and arrives at the point of focus at **528**.

Because the adaptive reflector array **575**, in conjunction with projector **440**, can produce real images at any depth of focus from calculations derived from virtual objects, the eye should not be able to distinguish the difference between a real and virtual depth of focus. The images will appear just as real, and the crystalline lens will accommodate to the appropriate focus just as if it were produced by a real object.

In this one example, the adaptive reflector array **575** is comprised of single DOF steerable optical elements. That is, the rotation axis of any steerable optical element is normal to any vertical plane of cross section having point **510** in common. This may be insufficient to produce the full range of optical properties, angles, and depths of field for the most general virtual scene. In addition, in order to produce a spot size on the retina of 5 microns, representing 20/20 visual resolving power, then it would be desirable to steer, in a coordinated fashion, a beam of approximately 2.5mm in diameter. Also, if viewer astigmatism or any other off axis optical errors are in need of correction, then an array of two DOF or three DOF steerable optical elements can be employed. In the most general case then, an adaptive optical reflector **575**, composed of two DOF or three DOF steerable optical element arrays would provide for a corrected, real image, with full binocular cues and a true depth of field requiring crystalline lens accommodation for a total sense of visual immersion.

The methodology for projecting a real, near field image from a virtual object is as follows.

1. Define a spherical surface S of radius R_i , centered on the pupil, where R_i is initially the closest desired focal distance in front of the viewer.
 2. Find the intersection between the virtual scene components and the surface of sphere S.
 3. Calculate the proper intensity, color, location, and direction of all light beams produced by the virtual object.
 4. Calculate the tilt angles of all steerable optical elements on adaptive reflector array **575** to simulate the virtual elements found in steps 2 and 3.
 5. Actuate those steerable optical elements and project the calculated beams from scanning projector **440**, onto those elements only.
 6. Increment R_i by a small amount (move the cross section of the virtual object further away).
 7. Repeat the full process from step 1 forward until the full front to back scan is complete.
- OR --
1. Repeat steps 1 through 5, but scan all areas of the adaptive reflector array **575**, thereby including distant imagery with near objects during a single projection.
 2. Continue with steps 6 and 7 as above.

Figure 16 shows a single degree of freedom V-Gap Optical Element. The optical surface, **571**, can take the form of a simple micromirror, a multilayer dielectric stack, a metamaterial, an optical grating array, a static convex or concave optical element, an actively variable concave or convex optical element, or any other optical element that can transmit, absorb, upconvert, downconvert, lase, emit, refract or reflect electromagnetic radiation.

In this embodiment, the VGOE is composed of an optical surface **571** that is supported by an upper substrate **572** that can be controllably opened to a v-gap angle **578** relative to a lower substrate **574**. In one configuration, a controllable, antagonistic force is established between hinges **580** and an electrostatic force provided by charges present on the actuator surface **570** of upper substrate **572** and actuator surface **576** on lower substrate **574**. If v-gap angle **578** is zero when the device is inactive, then the controlled introduction of like charges on actuator surfaces **570** and **576** will cause the v-gap angle to increase, overcoming the closing forces of hinges **580**. If hinges **580** normally force the upper substrate **572** into a positive v-gap angle **578** with respect to lower substrate **574** with no charges present on surfaces **570** and **576**, then the

introduction of opposite charges placed on actuator surfaces **570** and **576** will provide a v-gap closing force to overcome the hinge **580** opening forces. In either case, a precise v-gap angle **578** can be established by controlling the charges present on actuator surfaces **570** and **576**.

It can be appreciated that magnetic forces could be substituted for electrostatic forces thereby producing the same control of v-gap angle **578**. Equivalently, hinges **580** could be comprised of a thermal bimorph, a piezoelectric bimorph, or a shape memory element, thereby providing an opening or closing motion to control v-gap angle **578** without the use of electrostatic or magnetic driving forces. In this example, the variable capacitance established by the two actuator surfaces **576** and **570**, could provide a voltage feedback signal to actively control v-gap angle **578**. Similarly, any optical, magnetic, thermal, electrical, mechanical, stress, or strain sensing circuits monitoring hinges **580** or of v-gap angle **578** could also provide a feedback signal to precisely control the gap angle.

Optical surface **571** could take the form of an optical grating that produces bright colors from reflected white light wherein the reflected wavelength is dependent on the relative angle between the grating, the light source and the observer. In another embodiment, the frequency output of optical grating **571** could be controlled electronically wherein the spacing between each successive ruling can be varied. In yet another embodiment, various colors might be produced using an electronically variable thin film interference device wherein an electronically controlled gap between a transparent or translucent upper surface and a reflective lower surface is provided. The controllable gap might be a vacuum gap in one configuration or a media filled gap in a multitude of alternate configurations. In other configurations, the color of optical surface **571** could be controlled by magnetically, electrically, optically, or thermally varying a spectrally dependent reflecting micro structure.

The hinge area of one possible configuration of a Single DOF VGOE is shown in figure 17. Given an electrically insulating substrate **574**, a conductive layer **576** is deposited, patterned and is addressable via electronic circuitry. A sacrificial layer (not shown for clarity) and an additional insulating layer are then deposited and patterned to form the cantilever support bar **590** and insulating upper substrate **572**. A controlled etch **586**, is then applied to all hinge areas to adjust the overall thickness of **572** in the hinge area. This will have the effect of adjusting the spring rates of the final hinge layer areas represented by **588** and **594**. Any number of hinges **580** may support a v-gap optical element. Providing a stress gradient across the thickness of insulating upper substrate **572** with various deposition techniques also allows a controlled etch **586**, to move variable angle **578** to a chosen static position, when the device is inactive. Actuator layer, **570** may be deposited and patterned as before and may be electronically activated via address bar **592**. An additional insulating layer (not shown) may be deposited over **570** followed by optical layer **571**. Any number of actuator and optical layers may be fabricated on upper substrate **572**, and may communicate with address bar **592** and external electrical circuits via areas of conduction represented by hinge area **596**. Once all layers have been patterned, the sacrificial layer is removed, thereby freeing upper substrate **572**, and allowing it to move to its static position.

A small cross section of adaptive optics reflector array **575** is shown in figure 18. In this particular image, a small length of a single column of SDOF VGOEs is disposed on reflector body **442**. In practice, this small array would continue in a linear fashion for perhaps hundreds or tens of thousands of elements. An entire adaptive reflector array **575** would then be composed of perhaps hundreds or tens of thousands of such columns placed side by side forming the approximately conic adaptive reflector array **575** and shown in isometric view **906** in figure 27.

Two SDOF VGOEs, **602** are shown in a fully closed state. Their optical surfaces are nearly parallel to the local surface of adaptive reflector array **575**. SDOF VGOEs **600**, **565** and **560** are shown driven to various precise angles **598**, **604**, and **606** respectively. In this way, the exact deflection angle of an impinging light ray will be controlled at each point on the surface of adaptive reflector array **575**. With SDOF VGOEs, the rotation axis of any steerable optical element is normal to any vertical plane of cross section having point

510 in common (see figure 15). The family of normal vectors exiting the surface of each optical element may be overly constrained for some applications such that an image wave front cannot be properly represented. Thus, a multi DOF optical element would replace a single DOF element in this instance. A combination of single and multi DOF optical elements could be utilized on the same adaptive reflector array **575** substrate.

Figure 19 shows a Variable Focus Optical Element Array **625**, composed of an array of VFOEs **615**, as described in Figures 4, 5 and 6. Each VFOE is connected to its neighbor in a semi-rigid manner such that the optical axis of each VFOE is somewhat aligned with respect to its neighbors. The optical surfaces of each VFOE can vary in curvature. In particular, VFOE **620** is in the inactive state producing a flat surface. In one possible example utilizing electrostatic actuation, VFOE **635** has opposite charges on its upper and lower surfaces, thus, the diaphragm surface assumes a concave shape. And VFOE **630** has been activated with like charges and its surface has assumed a convex shape.

Depending on the size of an individual VFOE, an array can shape individual beams to be less or more divergent. A VFOE array can also shape wave fronts and image planes for any predefined activation pattern across the array. The surface deformation at each point of the array can be dynamically focused for purposes of beam and image shaping. The overall curvature of VFOEA **625** can take the form of a conic reflector, a hemisphere, a convex reflector, a flat surface or any other predetermined shape.

Figure 20 shows a single steerable Variable Focus Optical Element in a convex state. In this particular embodiment, a VFOE **656**, is similar in function to VFOE **615**, and is configured to be suspended in a double gimbal frame configuration and constrained by two pairs of gimbaled torsion bearings, **654** and **672**. Each bearing pair restrains vertical movements while permitting torsional movements with a single DOF. Conductive lines providing electrical communication to actuator pads **658A**, **658B**, **658C**, **658D** from the outside world, as well as electrical communication to optical surface **630**, are in contact with, and pass over these gimbal bearings. In this example, the optical surface **630** has been activated to a convex state.

Actuator pads **658A**, **658B**, **658C**, and **658D** are arranged on the four surface corners of VFOE **656** to provide unbalanced actuation forces that can rotate VFOE **656** with two DOF about the rotation axis defined by gimbaled torsion bearings **654** and **672**. If acting in pairs, actuator pads **658A** and **658B** can counter or enhance the rotation forces produced by **658C** and **658D** causing a pure rotation about an axis defined by gimbal bearing pair **654**.

An outer gimbaled frame **660**, holds the inner gimbaled VFOE **656**, and permits rotation about the axis defined by gimbal bearing pair **654**. A fixed outside frame **670**, permits rotation of frame **660** about a second axis of rotation that is substantially orthogonal to the first, and defined by gimbal bearing pair **672**. All electrical paths must travel over or upon this second set of gimbal bearings, **672**. Actuator pads **676** (lower pads not shown due to obscuration) may provide electrostatic forces for rotating the inner gimbaled optical element **656** to a predetermined angle about gimbal bearing **672**'s axis of rotation.

As before, magnetic, thermal bimorph, thermal expansion, local optical heating, piezoelectric, shape memory deformation or a host of other forces could also be substituted to provide angular or linear displacement in a similar fashion.

Figure 21 shows a single steerable Variable Focus Optical Element in a concave state, similar to the discussion of figure 20, but with VFOE **680** in a concave state. In this one example, VFOE **680** is torsionally constrained by a set of gimbaled torsion bearings **654** to outer gimbal frame **660** and outer gimbal frame **660** is torsionally constrained by a sets of gimbaled torsion bearings **672** to an externally fixed frame **670**. Rotation forces, communication lines, actuator pads and alternative force producing methods are similar to the discussions of figure 20. It can be appreciated that in the most general sense, the method of gimbaled connections, the relative direction of their axes of rotation, and the external shape of the elements themselves can take many different physical forms.

It can be noted that a half ball micro lens or a vertical GRIN lens, or any other refracting lens could be fabricated or attached to a flat mirrored surface thereby providing steerable focusing power as well.

Figure 22 shows an array of steerable Variable Focus Optical Elements in a concave state. Individual beam steering elements **680**, can take the form of a dynamic VFOE, or can be statically defined by the fixed curvature of each optical surface. Individual elements can take any curvature. The array **670**, can be configured for controlled single DOF motion, two DOF motions, or a combination of the two. The outer fixed frame portion of array **670** will generally be formed into a conic reflector, but can take any general shape.

A concave point reflector profile is advantageous for the reflection of small diameter laser beams, as unavoidable divergence due to diffraction is inversely proportional to beam diameter and must be maintained with positive focusing elements, if a small spot size is desired at a close distance. The average size of a photoreceptor is approximately 6 microns. And the smallest resolvable angle for the human eye with 20/20 vision is approximately 60 seconds of arc. Therefore, if 20/20 resolving power is the goal, then for example, a 2.5 mm diameter beam must be collimated to approximately one degree of divergence to form a 5 micron spot on the retina with a crystalline lens **408** focal length of approximately 17.1 mm. A point source distance of 6 inches from the cornea represents a beam divergence of approximately 1 degree.

Shown in Figure 23 is a double gimbaled, flat optical array. Other than the central optical element, all features and operations are similar to the arrays previously discussed. In one embodiment, the optical surface, **682** of all beam steering elements **680** are in a flat state. This can be achieved by the dynamic control of a VFOE or by the use of a statically defined flat surface. As before, substrate **670** is fixed with respect to outer gimbaled frame **660**. A single DOF flat mirror state is quite useful in a reflector array designed for dynamic focusing of portions of the total reflector surface as described in Figure 15. Of course, beam steering elements **680** can be of any external shape including rectangular or square.

As before the optical surface **682**, can also take the form of a simple micromirror, a dynamic VFOE, a multilayer dielectric stack, a metamaterial, a static or dynamically controlled optical grating array, a static convex or concave optical element, or any other optical element that can transmit, absorb, polarize, upconvert, downconvert, lase, emit, refract or reflect electromagnetic radiation in any way. It must also be noted that the method of action should not be limited to electrostatic forces only. Magnetic, thermal bimorph, thermal expansion, local optical heating, piezoelectric, shape memory deformation or a host of other forces could also be substituted to provide angular or linear displacement in a similar fashion.

Figure 24 shows an array of metamaterial reflectors. Metamaterials have shown a promising potential for having the ability to vary n , a measure of their refractive coefficients. In the right configuration, an incident beam **735** can be electronically deflected by an angle **740** at one potential while incident beam **730** can be electronically deflected by an angle **725** at a different potential. The simple configuration shown, consists of a deliberately engineered thin film nano structure that can be made to alter the index of refraction at will. Small pads of index changing metamaterial, **702** are fabricated on substrate **700** and are isolated from one another by trenches **706**. Each metamaterial pad **702** is controlled by individually addressable control plates, **704** positioned beneath each pad **702** and upon substrate **700**.

Figure 25 shows a larger array of metamaterial beam steering plates **702** disposed on substrate **700** and lying directly over control plates **704**. The array can be made sufficiently large to accommodate a large visual field at high acuity. The upper limit of beam deflecting elements could be larger than the total number of photoreceptors in the human eye, or 15 million. Substrate **700** may take any 3D curved form, such as a conic, to provide the necessary beam forming properties as described in the figure 15 discussion and represented by adaptive reflector array **575**.

A Micro Scanner Direct Projection Optical Element **820**, is shown in figure 26. It consists of a scanning projector **440**, a compound lens **800**, with a corrective first surface nearest scanning projector **440** and a micro lens covered second surface nearest the eye **460**. The MSDPOE **820** is contained within an isolation container **802**, that provides support for elements **440** and **800**, and optical isolation from neighboring MSDPOEs. Electrical and optical signals are conveyed to each MSDPOE via the back surface of **802**. As with the Adaptive Optics Reflector Array **575** discussed in figure 18, a small column of MSDPDs, **835**, is shown in figure 26. By combining a sufficient number of projector columns side by side, a full vertical and horizontal field of view may be produced.

The function of the MSDPOE array is as follows. Precisely calculated divergently scanned beams of light **810**, are emitted by scanning projector **440**. These rays strike the back of lens **800** and are made nearly parallel after passing through the first surface. Beam divergence is then refined by the micro lens array, **825** on the front side of lens **800**, such that a small focus spot may be achieved on the retina. Each MSDPOE is rigidly affixed to its neighbor and produces projected rays **840**, that are canted in the proper direction to intercept the cornea, thereby producing a properly immersive scan directly on the retina. It may be noted, that beam **840** is approximately normal to the exit surface of lens **800** and may not depart at the proper angle for all simulated visual field conditions. To correct for this situation, one might employ the array of steerable flat optical elements **682** shown in figure 23. In this 2DOF implementation, one would simply replace the flat reflectors supported in the double gimbal frames with micro lenses. A general exit beam direction could then be achieved by introducing this beam steering array in place of the micro lens array **825**. It can be appreciated that the lens **800** and container **802** could form a scanning optical projector with any combination of refractive or reflective elements of any shape. For instance, scanning projector **440** could be placed on the back surface of **800** and directed towards a reflective surface defined by the inner wall of **802**. Said reflective wall of **802** might take the form of a near-parabolic reflecting surface **422** of figure 10. Rays **810** would then reflect off of this surface and pass through lens **800** as before. This is similar to the larger projector configuration of figure 12. Finally, by combining the function of the design found in figure 12, with the refractive steerability described above, one could provide a compact, micro scanner direct projection element **820** with a near ideal exit angle for any beam **840**.

Figure 27 shows a top view of the system integrating glasses **900** in the upper area and an isometric view of the glasses in the bottom part of the figure. The integrated system consists of a computer, power, and communications module, **910** that may combine all three functions into one. However, it is likely that a remote computational device, perhaps cloud based, would carry most of the load considering the current state of microcomputers, while the communications functions could adequately be handled in this volume. It can be appreciated that the computer and communications functions could all be located remotely from the glasses frame. A power source could be supported, but more likely, this too would be accessed off frame via a wire or with some other remote power delivery method. The scanning projectors **440** are shown for each of the left and right eyes. The scanned beams reflect off any variety of reflectors **906**, described herein. A comfortable, light isolation foam gasket **916**, would be replaceable and custom fit for each individual, incorporating a breathable, light baffling design. If needed, external eye tracking cameras placed on an angular ring **902**, could be provided to view the pupil in the usual way. The eye tracking cameras could also be placed on each reflector surface **906** if small enough to not be intrusive. External cameras, **426** are shown and if properly distributed on the outer surface and of high enough resolution, could provide video input to the wearer that would emulate what one would see if not wearing the glasses. This view could also be combined with purely synthetic images to give a sense of augmented reality. Corrective lens **908** also provides support for the scanning projectors **440**. Finally, an external view of one's eyes through each lens, as perceived by a passerby could be achieved by acquiring an image of the wearers eyes with an inward facing mini camera and projecting it on the external surface of **920** via a liquid crystal, LED or OLED, or any other display. To complete the full immersion effect, one or more speakers **905** in the form of earbuds, for example, could be incorporated into system integrating glasses **900**.

CLAIMS

1. An immersive optical projection device comprising:
a frame;
at least one projector array comprising
 at least one image projection device;
at least one light source, wherein said light source is coupled to said projector array;
a reflector,
 wherein said reflector is coupled to said frame; and
a projector array support,
 wherein said at least one projector array is coupled to said projector array support and said
 projector array support is coupled to said frame,
such that a beam of light produced by said at least one light source is directed to said at least one
image projection device, and said at least one image projection device controllably emits a
luminous image, in at least one dimension, that further proceeds towards said reflector,
whereupon, said reflector redirects said luminous image into an observer's eye.
2. The immersive optical projection device of claim 1 wherein said at least one image projection
device is a scanning sub-projector configured to controllably steer said at least one beam of light
with at least one degree of freedom.
3. The immersive optical projection device of claim 1 further comprising at least one beam
modulator placed in an optical path between said at least one light source and said observer's eye,
such that the amplitude, polarization state, wavelength, or degree of vergence of said beam of
light impinging on said at least one beam modulator is selectively altered and further proceeds
along said optical path.
4. The immersive optical projection device of claim 1 further comprising at least one observation
channel.
5. The immersive optical projection device of claim 1 wherein said at least one image projection
device is a multi-degree of freedom beam steering device.

6. The immersive optical projection device of claim 1 wherein said at least one projector array is a scanning projector.
7. The immersive optical projection device of claim 1 wherein said reflector is a revolved conic section having at least a partially reflective surface or a revolved asphere having at least a partially reflective surface.
8. The immersive optical projection device of claim 1 wherein said reflector is a refractive element having an at least partially reflective distal surface and a substantially transparent proximal surface such that said at least one beam of light passing through said refractive element and reflecting off said at least partially reflective distal surface is further directed towards said substantially transparent proximal surface and into said observer's eye.
9. The immersive optical projection device of claim 1 further comprising at least one integrated system module, wherein said at least one integrated system module is a data processor module, a power module, a wired communications module, a wireless communications module, an electro optical module, an inertial sensor module, a position sensor module, a speaker module, a camera module, or an eye tracking module, and said at least one integrated system module is coupled to said frame.
10. The immersive optical projection device of claim 1 further comprising:
at least one outward looking camera; and
at least one motion sensor,
wherein said at least one outward looking camera is affixed to a distal surface of said reflector and said at least one motion sensor is affixed to said frame.
11. The immersive optical projection device of claim 1 further comprising an array of individually controllable micromirrors disposed on a proximal surface of said reflector nearest said observer's eye, wherein each individually controllable micromirror of said array is configured to selectively control the angle of reflection of an impinging said beam of light.

12. The immersive optical projection device of claim 1 further comprising at least one said image projection device coupled to said frame such that said at least one image projection device controllably emits said luminous image, in at least one dimension, that further proceeds into said observer's eye.

13. The immersive optical projection device of claim 1 wherein said projector array support is a refractive corrector lens that is sealed against said reflector, thereby forming a sealed cavity protective of said reflector and said projector array, wherein said projector array is coupled to said refractive corrector lens and within said sealed cavity.

14. The immersive optical projection device of claim 1 further comprising a variable focus optical element array disposed on a proximal surface of said reflector nearest to said observer's eye, wherein each variable focus optical element of said variable focus optical element array is configured to control the vergence of an impinging beam of light.

15. An immersive optical projection device comprising:

a frame;

at least one scanning projector, wherein said at least one scanning projector is further comprised

of at least one multi-degree of freedom steerable micromirror;

at least one light source, wherein said light source is coupled to said scanning projector;

a revolved conic section reflector surface or aspheric reflector surface;

an array of individually controllable micromirrors, wherein said array of individually

controllable micromirrors is disposed on said revolved conic section reflector surface or said aspheric reflector surface; and

a refractive element coupled to said frame,

wherein said refractive element is sealed against said revolved conic section reflector surface or said aspheric reflector surface, thereby forming a sealed cavity protective of said revolved conic section reflector surface, or said aspheric reflector surface and said at least one scanning projector,

wherein said at least one scanning projector is coupled to said refractive element and within said sealed cavity,

such that a beam of light produced by said at least one light source is directed to said at least one multi-degree of freedom steerable micromirror, and said at least one multi-degree of freedom steerable micromirror controllably emits a luminous image, in at least one dimension, that further proceeds towards said array of individually controllable micromirrors, and is further directed through said refractive element into an observer's eye.

16. An immersive optical projection device comprising:

a support structure;

at least one micro scanner direct projection optical element comprising:

at least one light source;

at least one multi-dimensional image projection device; and

a projection optical element,

wherein said at least one multi-dimensional image projection device is coupled to said support structure,

and said at least one light source, said at least one multi-dimensional image projection device and said projection optical element are coupled with respect to one another such that a beam of light produced by said at least one light source is directed to said at least one multi-dimensional image projection device, and said at least one multi-dimensional image projection device controllably emits a luminous image in at least one dimension, that further proceeds through said projection optical element, whereupon said luminous image is projected towards an observer's eye.

17. The immersive optical projection device of claim 16 further comprising:

a light isolation housing,

wherein said at least one multi-dimensional image projection device is affixed to an interior wall of said light isolation housing and said projection optical element is sealed against an opposing open side of said light isolation housing, such that a sealed cavity protective of said at least one multi-dimensional image projection device and one side of said projection optical element is formed,

such that said luminous image emitted by said at least one multi-dimensional image projection device passes through said projection optical element and away from said light isolation housing towards said observer's eye.

18. The immersive optical projection device of claim 16 wherein said at least one multi-dimensional image projection device is a scanning projector that can steer said beam of light with at least one degree of freedom.

19. The immersive optical projection device of claim 16 further comprising at least one beam modulator placed in an optical path between said light source and said observer's eye, such that the amplitude, polarization state, wavelength, or degree of vergence of said beam of light impinging on said at least one beam modulator is selectively altered and further proceeds along said optical path.

20. The immersive optical projection device of claim 16 wherein said at least one micro scanner direct projection optical element comprises a plurality of micro scanner direct projection optical elements arrayed in two dimensions on surface of said support structure such that a screen of sufficient size is created for direct viewing by one or more observers.