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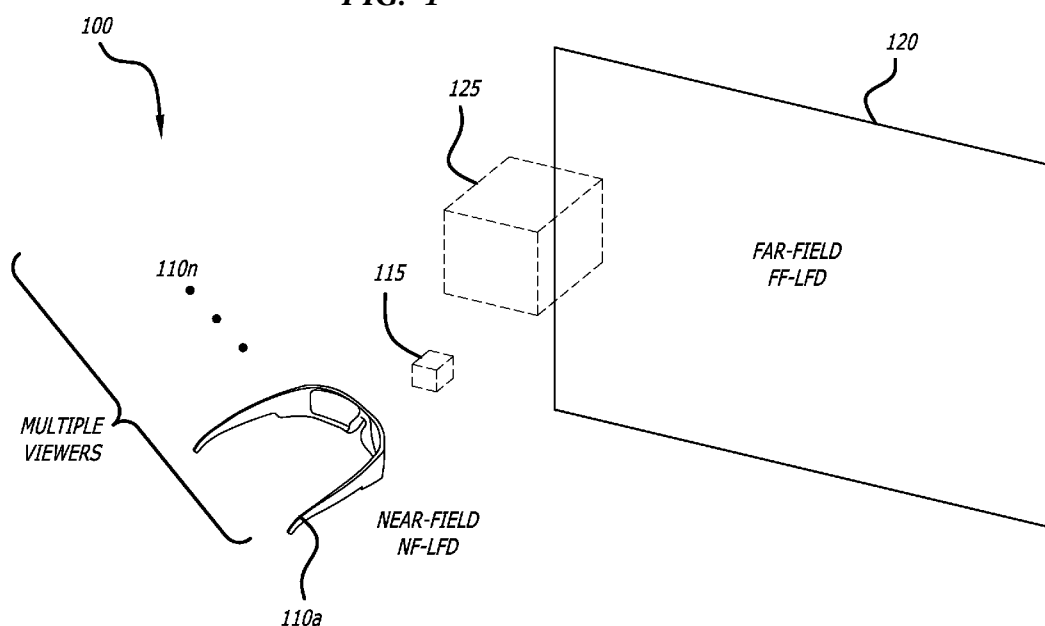
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(54) Title: INTEGRATED NEAR-FAR LIGHT FIELD DISPLAY SYSTEMS

FIG. 1



(57) Abstract: Complementary near-field and far-field light field displays (LFDs) are provided. A distributed LFD system is disclosed in which the light field is cooperatively displayed by a direct view LFD and a near-eye LFD. The two display components of the system work together synchronously to display a high-fidelity 3D experience to one or multiple viewers.

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INTEGRATED NEAR-FAR LIGHT FIELD DISPLAY SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 62/329,111, filed April 28, 2016, the entirety of which is incorporated herein by reference.

FIELD

[0002] One aspect of the present disclosure generally relates to near-eye displays, augmented reality displays, and light field display systems.

BACKGROUND

[0003] Light field displays that allow a viewer to focus at will on objects at various depths of a scene are poised to become more commonplace and have a wide number of commercial and consumer applications. For example, light field displays may be used in near-eye display and augmented reality applications, as well as in direct view applications enabling a multiplicity of viewers to focus on different or the same objects in a scene. Currently, it is often difficult for conventional light field display solutions to provide a uniformly high resolution viewing experience for viewing objects at various depths within the light field.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] The embodiments herein are illustrated by way of example and not by way of limitation in the figures of the accompanying drawings in which like references indicate similar elements. It should be noted that references to "an" or "one" embodiment in this disclosure are not necessarily to the same embodiment, and they mean at least one.

[0005] In the drawings:

[0006] FIG. 1 illustrates an example for explaining an integrated light field display system for display of near and far segments of a light field according to an embodiment.

[0007] FIGS. 2A to 2C illustrate examples for explaining an optical modulation transfer function (MTF) of a light field display according to an embodiment.

[0008] FIG. 3 illustrates an example for explaining an integrated light field display system in a mobile environment according to an embodiment.

[0009] FIG. 4 illustrates an example for explaining a collective light field volume of the integrated light field display system of the embodiment of FIG. 3.

[0010] FIG. 5 illustrates an example block diagram for explaining the integrated light field display system of the embodiment of FIG. 3.

[0011] FIG. 6 illustrates an example for explaining a coordinate system used by a light field processor (LFP) of the integrated light field display system of the embodiment of FIG. 3.

[0012] FIG. 7 illustrates an example for explaining an integrated light field display system in a workstation environment according to an embodiment.

[0013] FIG. 8 illustrates an example for explaining an integrated light field display system in an automotive environment including a head-up display (HUD) according to an embodiment.

[0014] FIG. 9 illustrates an example for explaining an integrated light field display system in a home entertainment environment according to an embodiment.

[0015] FIG. 10 illustrates an example for explaining an integrated light field display system in a cinematic entertainment environment according to an embodiment.

DETAILED DESCRIPTION

[0016] The present disclosure and various of its embodiments are set forth in the following description of the embodiments which are presented as illustrated examples of the disclosure in the subsequent claims. It is expressly noted that the disclosure as defined by such claims may be broader than the illustrated embodiments described below. The word "exemplary" is used herein to mean serving as an example, instance, or illustration. Any aspect or design described herein as "exemplary" is not necessarily to be construed as preferred or advantageous over other aspects or designs.

[0017] In one aspect of the disclosure herein, near-eye light field augmented reality light field displays are integrated with direct view light field displays to provide a viewer with an improved visual experience. With respect to light field displays, a new class of emissive micro-scale pixel array imager devices has been introduced as disclosed in U.S. Patent No. 7,623,560, U.S. Patent No. 7,767,479, U.S. Patent No. 7,829,902, U.S. Patent No. 8,049,231, U.S. Patent No. 8,243,770, U.S. Patent No. 8,567,960, and U.S. Patent No. 8,098,265, the contents of each of which is fully incorporated herein by reference. The disclosed light emitting structures and devices referred to herein may be based on the

Quantum Photonic Imager or "QPI®" imager. QPI® is a registered trademark of Ostendo Technologies, Inc. These disclosed devices desirably feature high brightness, very fast multi-color light intensity and spatial modulation capabilities, all in a very small single device size that includes all necessary image processing drive circuitry. The solid-state light- (SSL) emitting pixels of the disclosed devices may be either a light emitting diode (LED) or laser diode (LD), or both, whose on-off state is controlled by drive circuitry contained within a CMOS chip (or device) upon which the emissive micro-scale pixel array of the imager is bonded and electronically coupled. The size of the pixels comprising the disclosed emissive arrays of such imager devices is typically in the range of approximately 5-20 microns with a typical emissive surface area being in the range of approximately 15-150 square millimeters. The pixels within the above emissive micro-scale pixel array devices are individually addressable spatially, chromatically and temporally, typically through the drive circuitry of its CMOS chip. The brightness of the light generated by such imager devices can reach multiple 100,000 cd/m² at reasonably low power consumption.

[0018] The QPI imager is well-suited for use in the light field displays, both for near-eye augmented reality as well as direct view light field displays, described herein. See U.S. Patent No. 7,623,560, U.S. Patent No. 7,767,479, U.S. Patent No. 7,829,902, U.S. Patent No. 8,049,231, U.S. Patent No. 8,243,770, U.S. Patent No. 8,567,960, and U.S. Patent No. 8,098,265. However, it is to be understood that the QPI imagers are merely examples of the types of devices that may be used in the present disclosure, which devices may, by way of a non-limiting set of examples, include OLED, LED, micro-LED imaging devices. Thus, in the disclosure herein, references to the QPI imager, display, display device or imager are to be understood to be for purposes of specificity in the embodiments disclosed, and not for any limitation of the present disclosure.

[0019] Turning to FIG. 1, FIG. 1 illustrates one example of an integrated light field display system comprising multiple light field display elements that collectively collaborate to display near and far segments of a light field. In particular, FIG. 1 illustrates a first example in which an integrated light field display system 100 includes a direct view light field display 120 modulating a far segment of a light field (LF) and a multiplicity of near-eye light field displays 110 (individually near-eye light field displays 110a-110n) displaying the light field segments near to each viewer. In one embodiment, the near-eye light field display (LFD) components 110 may each operate as an augmented reality light field display (AR LFD) that may comprise a set of optical see-through (OST) glasses. In one embodiment,

the optical see-through glasses may include both eye and head tracking capabilities and may be able to obtain information regarding a viewer's eye gaze direction, interpupillary distance (IPD) and head orientation. For example, the optical see-through glasses may comprise at least one eye-tracking sensor per eye to detect multiple parameters of the viewer's eyes including but not limited to the angular position (or look angle) of each eye, the iris diameter, and the distance between the two pupils (IPD). As one example, the eye-tracking sensors may be a pair of miniature cameras each positioned to image one eye. In one embodiment, the eye-tracking sensors may be placed in a non-obstructive position relative the eyes' field of view (FOV) such as the bridge section of the frame of the glasses. The eye-head tracking component may be configured to detect, track and predict where the viewer's head is positioned and where the viewer is focused in depth and direction within the collective light field volume. One example of a head and eye tracking system is shown in FIG. 5, as HVS tracking sensor 503.

[0020] The multiple AR LFD elements 110 may be interconnected together via a wireless local area network (W-LAN) or wireless personal area network (W-PAN) and may also be connected to the internet to enable streaming of light field content to be displayed in their collective light field volume. Another component of the integrated light field display system 100 is a light field processor (LFP) that is communicatively coupled, either wirelessly or via wire, to the other components of the integrated light field display system 100 including the multiplicity of AR LFD elements 110. In one embodiment, the light field processor may also be connected to a memory block that can be implemented via one or more memory devices including volatile storage (or memory) devices such as random access memory (RAM), dynamic RAM (DRAM), synchronous DRAM (SDRAM), static RAM (SRAM), or other types of storage devices. The light field processor may be implemented in software, hardware, or a combination thereof. For example, the light field processor can be implemented as software installed and stored in a persistent storage device, which can be loaded and executed in a memory by a processor to carry out the processes or operations described throughout this application. The light field processor may represent a single processor or multiple processors with a single processor core or multiple processor cores included therein. The light field processor may represent a microprocessor, a central processing unit (CPU), graphic processing unit (GPU), or the like. The light field processor may be a complex instruction set computing (CISC) microprocessor, reduced instruction set computing (RISC) microprocessor, matched instruction set microprocessor (MISP), very

long instruction word (VLIW) microprocessor, or processor implementing other instruction sets, or processors implementing a combination of instruction sets. The light field processor can also be implemented as executable code programmed or embedded into dedicated hardware such as an integrated circuit (e.g., an application specific IC or ASIC), a digital signal processor (DSP), or a field programmable gate array (FPGA), which can be accessed via a corresponding driver and/or operating system from an application. The light field processor may be a cellular or baseband processor, a network processor, a graphics processor, a communications processor, a cryptographic processor, an embedded processor, or any other type of logic capable of processing instructions. Furthermore, the light field processor can be implemented as specific hardware logic in a processor or processor core as part of an instruction set accessible by a software component via one or more specific instructions.

[0021] In one embodiment herein, the light field processor is cognizant of the position of each display element and computes the light field contribution 115 of each display element to the collective light field volume. In one embodiment, the light field processor visually articulates the appropriate portion of the integrated light field based on the viewers' visual and/or gesture cues to modulate that light field segment at the highest possible optical performance. Each of the AR LFD components 110 may include a wearable gesture sensor to enable the viewer to interface and interact with the light field. Each of the AR LFD components 110 may alternatively include a gesture tracking sensor incorporated within AR LFD 110 assembly to enable the viewer to interface and interact with the light field and the AR LFD. Each of the AR LFD components 110 may incorporate optical and display elements that enable optical see-through (OST) high fidelity performance to provide high quality visual performance of the light field displayed by the AR LFD as well as the (complementary) light field that is being displayed by a far-field (FF) LFD display 120. The AR LFD provides viewer focus-ability of near-field objects at a high-resolution level and incorporates light field compression and visual decompression techniques that enable a lightweight and low power system. The AR LFD disclosed herein may include both visual and location sensors, such as an inertial measurement unit (IMU) for example, that "localize" the viewer within the total light field volume of the system.

[0022] In one embodiment, the AR LFD components 110 of the system may also include a simultaneous localization and mapping (SLAM) capability to assist in locating the viewer within the display light field volume more accurately and in real-time.

[0023] In one embodiment, the AR LFD components 110 of the system may have an angular resolution that approaches human vision system acuity limits and make it possible to give the viewer as close as possible, a real-world viewing experience of the near light field.

[0024] The far-field (FF) portion of the light field of the system 100 may be configured to be displayed or modulated by the direct view light field display component (FF LFD) 120 of the system incorporating sufficient light field modulation capabilities to permit the display of the light field to viewers within a large viewing distance (light field depth) ranging from about 1m to 10m viewing distance as the background light field yet remain focusable by the viewer's optical see-through (OST) AR LFD as the ambient reality being augmented by the AR LFD component 110 of the system. The integrated light field display system 100 may decide whether the far field LFD (e.g. FF LFD 120) or the near field LFD (e.g. AR LFD, also referred to herein as an NF LFD) 110 provides the best viewing experience to the viewer. In order to make that decision, the integrated light field display system 100, and in particular the light field processor, may compute one or a predetermined set of optical performance light field characteristics such as resolution or a spatial or angular modulation transfer function (MTF) as a performance metric of each of the light fields being modulated by both components of the system where the viewer is focused and the light field data may be routed to the LFD components. The MTF may consider the spatial or angular frequency response of the light field display, and may also consider both the spatial and angular frequency response of the light field display). The integrated light field display system 100 may command one or more of the LFD components (e.g., NF LFD 110 and FF LFD 120) having the best MTF performance to modulate (or display) the segment of the light field being focused upon by the viewer. For example, if the viewer is focused on a FF object 125, the computed MTF where the viewer is focused would be highest when that LF portion surrounding the object 125 is modulated by the FF LFD 120 and the integrated LFD system 100 may route the data pertaining to that portion of interest of the light to be modulated to the viewer via the FF LFD component 120. Similarly, if the viewer is focused on a NF object 115, the computed MTF where the viewer is focused would be highest when that LF portion surrounding the object 115 is modulated by the NF LFD 110 and the integrated LFD system 100 may route the data pertaining to that portion of interest of the light to be modulated to the viewer via the NF LFD component 110. In both cases, while the selected light field display modulates the portion of the light field where the viewer is focused at the highest optical performance (e.g., MTF) possible, the complementary light field display modulates

the rest of the light field as a background ready to be focused upon (or focusable) by the integrated LFD system viewer. The integrated LFD systems and methods described herein therefore provide the system user with the highest possible optical performance in viewing an integrated (or extended) light field volume covering the complementary LF volumes of its constituent LFD components. The integrated LFD system's action in providing the highest possible optical performance, and therefore the best possible viewing experience, are viewer-driven very much in a similar way as the viewers naturally focus on their surroundings.

[0025] With this approach, the overall system performance (3D focusable viewability) is shared (divided) and provided by the near field (NF) and far field (FF) LFD components of the system. Viewable light field depth (volume) in particular can be substantially large while maintaining a high fidelity viewing experience of both near and far objects within the integrated display system light field volume. Since the AR LFD component 110 is near the viewer's eye and is capable of obtaining the viewer's eye gaze direction, interpupillary distance (IPD) and head orientation, near field objects can be displayed to each one of multiple viewers simultaneously at tractable computational loads given the light field segmentation possible by the distributed aspects of the system.

[0026] With the distributed aspects of the integrated NF LFD system disclosed herein, as many as 8-16 views AR LFD and 128-256 views FF LFD components, for example, can be used to provide an experience far exceeding that of 4096 views of a direct view LFD yet with each component being computationally feasible (tractable) by virtue of the distributed computation aspect of the integrated LFD system disclosed herein. It is therefore possible for the near field (NF) and far field (FF) components of the integrated LFD system to computationally complement each other to provide a superior viewing performance experience for the viewer.

[0027] In addition, with the distributed optical aspects of the integrated LFD system disclosed herein, it is possible to have the FF LFD operate at a lower resolution (which enables more views at a wider field of view (FOV) coverage) while the AR LFD component, by virtue of its eye/head tracking capability, provides complementary fine resolution to fill in the coarse light resolution provided by the FF LFD component. It is therefore possible for the near field (NF) and far field (FF) components of the integrated LFD system to optically complement each other in terms of viewing performance experienced by the viewer.

[0028] In leveraging the viewer's localization capabilities of the integrated LFD system disclosed herein, it is possible to dynamically adjust the number of views being modulated by the FF LFD to match the number and location of the viewers engaging the system, thus introducing power consumption and compression benefits. The system can track and accommodate multiple viewers simultaneously.

[0029] FIGS. 2A and 2B illustrate the optical modulation transfer function (MTF) performance of an exemplary light field display. FIGS. 2A and 2B illustrate the light field display MTF performance metric expressed spatially and angularly; respectively, relative to the distance of the viewer's focus point from the light field modulation surface. In FIGS. 2A and 2B, the positive axis indicates the viewer's focus point being within the front region of the light field modulation surface while the negative axis indicates the viewer's focus point being within the back region of the light field modulation surface. As illustrated, the optical MTF of the displayed light field is typically at its highest value in the vicinity (e.g., front and back regions) of the light field modulation surface and decreases systematically for regions of the modulated light field farther away from the light field modulation surface. The trend illustrated in these FIGS. 2A and 2B, which show strong dependence of the light field MTF performance on the distance from the modulation surface, is used to determine the ultimate useful volume of the modulated light field. For direct view light field displays, the trend limits the viewer's near-field MTF. For near-eye light field displays, the trend limits the viewer's far-field MTF.

[0030] In terms of performance, a direct view LFD may struggle to achieve an acceptable optical modulation transfer function (MTF) further away from the display surface. A near-eye LFD may also have a good MTF for viewing objects near the viewer's eye but may struggle to achieve an acceptable MTF for objects far away from the viewer's eye. In both cases, a compromise design that aims to achieve higher MTF away from the modulation surface may compromise the 3D viewing resolution or granularity of the viewed objects. With the integrated near field/far field light field displays described herein, each component of the system is used at its performance "sweet spot". When the viewer focuses on a nearby object, the system handles the modulation of the LF within the volume surrounding that viewable object using or through the viewer's AR LFD thus presenting the viewer the best achievable optical transfer function (OTF) performance or MTF of that object. At the same time, the system uses the FF LFD to modulate the rest of the light field viewed by the viewer and to possibly coarsely (e.g., blurred details) modulate the light field background which

remains viewable through the OST capabilities provided by the AR LFD component of the system. On the other hand, if the viewer focuses on an object far away from the viewer's eye, for example near or behind the FF LFD modulation surface, then the system provides enough views or perspectives that allow the viewer's eye to accommodate through the OST capabilities of their AR LFD while achieving high MTF since the viewed object is now in the performance "sweet spot" of the FF LFD.

[0031] It is important to note from FIGS. 2A and 2B that a specified MTF limit value, for example $MTF > 10\%$ as indicated by the MTF lines in FIGS. 2A and 2B, defines a larger light field volume when the MTF is expressed angularly rather than spatially. Since the human visual system (HVS) depth perception is intrinsically angular, expressing the MTF metric of the integrated light field display disclosed herein angularly is more meaningful in terms of indicating HVS perceptual limits. FIG. 2C illustrates the MTF performance of the integrated light field display according to an embodiment herein with an AR LFD component (dotted line) located approximately 30cm from the direct view LFD component (solid line). It should be noted that the light field modulation surface for the AR LFD component is the eye-box of the display while for the direct-view LFD component it is its display surface. As can be seen from FIG. 2C, the integrated light field display in this embodiment achieves 0.5 lp/mrad $MTF > 50\%$ across a light field volume extending more than 50cm from the AR LFD component eye-box with that light field volume extending to almost 100cm with 0.5 lp/mrad $MTF > 10\%$. The cooperative light field modulation aspect of the integrated light field display is readily demonstrated in FIG. 2C which illustrates how the AR LFD and direct-view LFD components of the integrated light field display complement each other from the near to the far depth of the light field volume while achieving higher MTF performance over a more extended volume than what can be achieved by either of the system's LFD components.

[0032] Angular Partition:

[0033] In one embodiment, to implement the cooperative light field modulation scheme disclosed herein, the FF LFD modulates the light field with large angular resolution leaving the finer angular resolution to be "filled in" by the AR LFD. In this manner, the modulation pixels of the FF LFD can be beneficially dedicated to increasing the field of view (FOV) rather than the number of views. In this embodiment, the entire light field volume is coarsely (at a low angular resolution) modulated by the FF LFD and, when the viewer focus depth or vergence is detected by the AR LFD eye/head tracking sensor, the object is brought

into fine angular resolution that is achieved by the LF modulation capabilities of the AR LFD component of the system.

[0034] Volumetric Partition:

[0035] In one embodiment, to implement the cooperative light field modulation scheme disclosed herein, the overall light field volume is partitioned into a far-field segment which is modulated by the direct view FF LFD component and a multiplicity of near-field segments, each possibly centered around one of the system viewers. As any of the viewers focus on a far-field object, they would be focusing on what is being displayed or modulated by the FF LFD component of the system. As one of the viewers focuses on a near-field object, that object would be modulated by that view AR LFD component of the system associated with that viewer. In this embodiment, the entire light field is partitioned volumetrically rather than the angularly as in the aforementioned embodiment. In both cases, what is being viewed or perceived by the viewer is the result of the combined light field modulated by both components of the integrated LFD system.

[0036] An advantage of the disclosed LFD system is its distributed light field modulation aspects; both optically and computationally. Besides the significant optical performance that it achieves (see preceding discussion of FIG. 2C), this feature significantly alleviates the high processing throughput and memory requirements typical of LFD systems at that level of performance. In addition, the disclosed integrated LFD system enables a built-in light field compression within its distributed processing and LF modulation architecture. This becomes clear in that a direct view LFD must, by definition, enable a multiplicity of views within its LF modulation volume to be focused upon simultaneously by a multiplicity of viewers who may be focused on different or the same objects within the LFD volume from different perspectives (directions). Because of this fundamental requirement, the LFD volume must be able to provide the specified performance requirement in terms of MTF and viewing resolution uniformly across the entire light field display volume which, besides being a daunting task on its own in terms of optical and light field modulation design aspects, it is also daunting in terms of required processing and memory resources, especially given the performance expectations set forth by current 2D displays.

[0037] This challenge is dealt with in the integrated LFD system design disclosed herein by the segmentation of the light field, either volumetrically or angularly, and introduces a further major compression benefit in that the decompression and possibly rendering aspects are also segmented with the final decompression stage that leads to the

high fidelity viewing experience being performed based on viewers' access demands of the light field. This replicates the architecture of the human visual system (HVS) in which the finer resources of the system; namely, the approximately two (2) degree aperture of the central fovea part of the retina, is leveraged toward achieving the highest possible resolution for the focus part of the view while the low resolution remainder part of the retina is used to provide sufficient cognitive awareness of the view peripheral background.

[0038] The disclosed distributed LFD architecture follows similar strategy and extends the HVS eye pupil saccade approach in that it enables the user's saccade and focus action to derive the integrated LFD similar to how it derives the human cognitive perception capabilities, which is the processing-intensive portion of human reality perception interface. The disclosed distributed LFD architecture allows the system viewers to interact visually with the integrated light field volume of the system similar to the way viewers would typically focus on objects in their ambient surroundings; the light field modulation and processing being handled cooperatively by the distributed components of the LFD system disclosed herein. In addition, the LFD system disclosed herein brings into high resolution viewability the multiple portions of the light field that the system viewers are visually interacting with or focused upon. When the LFD system is being viewed by a single viewer, this approach is able to realize high levels of light field viewing performance using substantially fewer processing resources. When the LFD system is being viewed by multiple viewers, with this approach the processing resources needed to realize the high light field viewing performance scale up proportionally, but still in a distributed fashion.

[0039] That is to say in the LFD system disclosed herein, the processing-intensive resources of the system are geared or aligned with what the system viewers are attempting to acquire from the system - the system resources may then be used to enhance or provide a higher level of viewing experience to serve what the viewers seek rather than make a broader range of lower performance viewing potentials that consume system resources when such synthesized views may never be seen or perceived by any of the system's viewers.

[0040] This distributed LFD approach enables bringing high fidelity 3D display capabilities to mobile devices such as smart phones and tablets. The challenge here is obvious as the demands themselves are pronounced. The need for increased mobile visual bandwidth is widely recognized for keeping and sustaining business growth of mobile digital media providers.

[0041] To enable such capabilities, near-eye virtual reality (VR) and augmented reality (AR) displays are being explored as a platform. These platforms are sought in part because: 1) a direct-view LFD on a mobile device is not supportable using today's available display technologies; and, 2) assuming such technology eventually exists, it may not enable the reality augmentation aspects made possible by near-eye displays. The embodiments disclosed herein recognize that a higher performance near-eye display is rather challenging and that there is a risk that an underwhelming performance of such displays will put a damper on this aspect of growth of the mobile digital media industry.

[0042] The distributed LFD system described herein addresses these challenges and does so in conjunction with existing state of the art display technologies. As such, it is possible to enable high performance 3D capabilities in the mobile user environment that augment the display of the mobile device. It is also possible to make use of a direct-view display of the mobile device by making it work cooperatively with a mobile AR display, with the two components together used to implement a distributed LFD that enables high performance 3D viewing by mobile users, such that commercial growth potential is unleashed. The integrated light field display system of the embodiments herein may be realized by the direct view LFD of the mobile device working cooperatively with an AR display, each augmenting and complementing the other. The user may enjoy the best of both capabilities at a high performance, 1) the augmented reality with the background being the far-field, and 2) the mobile device itself being or synthesizing the far-field.

[0043] In addition, the disclosed LFD system can be implemented in a mobile shared viewing scenario with only the 3D display of the mobile device offering a limited FOV to cope with the excessive processing need of a large FOV, but with the light field content to be shared being viewable by a co-viewer connected to the LFD system described herein and the LFD volume being extended to enable sharing of the light field contents. As such, sharing the light field content of one viewer (the primary viewer) would be as simple as the co-viewer becoming connected to the LFD system to make his or her AR LFD become integrated with the primary viewer LFD system viewing volume and then visually interacting with (e.g., focusing on) the light field content to be shared.

[0044] The same is the case for tablets, laptop and desktop computers - the distributed LFD disclosed herein makes a high performance 3D experience possible on those platforms as well.

[0045] The same is also the case for cinematic viewing, gaming, command and control centers or commercial venue displays. In one embodiment, information from mobile users' AR displays is acquired by a large venue light field display to allow users wearing their AR display to experience a super-augmented reality as they walk by or sit in front of the large venue light field display, for example in a movie theatre.

[0046] Integrated Mobile LF Display:

[0047] FIG. 3 illustrates an embodiment of the integrated light field display system in a mobile scenario. In this embodiment, an integrated near/far light field display system 300 may comprise three display components, as illustrated in FIG. 3:

[0048] 1. A near-eye augmented reality (AR) display 310, such as a light field display or a device capable of displaying focusable three dimensional (3D) viewing contents;

[0049] 2. A mobile light field display 330 (e.g., mobile device or phone); and

[0050] 3. A wearable light field display 340 (e.g., smart watch).

[0051] All three LFD components of the system may be interconnected wirelessly (WL) using a personal area network (PAN) protocol together with a gesture sensing device integrated on the smart watch to add gesture control capability with the displayed light field volume.

[0052] The near-eye augmented reality (AR) light field display 310 may be worn by a mobile user on or near the user's head. The mobile light field display 330 may be a direct view light field display that is an integral part of a user's mobile smartphone or tablet device. The wearable light field display 340 may be an integral part of wrist worn device (e.g., smart watch). AR LFD 310 may incorporate a head and eye tracking sensor and interface capabilities. Wearable LFD 340 may incorporate a gesture sensor and interface capabilities. The three light field display elements and the two sensor elements may be interconnected via a wireless personal area network (WPAN) using interface capabilities incorporated as an integral part of each element. In order to reduce the light field processing throughput and memory requirements, and subsequently the power consumption requirements of the AR LFD 310 and wearable LFD 340, the light field processor (LFP) of the integrated light field system may be collocated together with the mobile light field display 330 within the mobile device or phone. Using the communication interface capabilities of its host mobile device or phone, the light field processor (LFP) may also be connected to the internet or cloud 350 via either a mobile wireless network or a wireless local area network (WLAN) 315, in order to further reduce the overall integrated light field display system processing throughput and

memory requirements and power consumption requirements by leveraging cloud computing performed possibly by the cloud server of the light field content provider. Based on position and orientation information sent by the three light field display elements through their wireless interconnects, which may be extracted from each mobile device's embedded position and orientation sensor, the light field processor (LFP) may compute the position and orientation of each of the three light field display elements relative to the light field volume 335 viewable by the mobile user. Through the integrated light field display system interconnectivity, the light field processor (LFP) obtains the position of each of the three display elements, computes the light field contribution of each of the display elements to the collective light field volume 335, and visually articulates the appropriate portion of the collective light field volume 335 based on the viewers' visual and/or gesture cues to modulate the respective light field segment at the highest possible optical performance.

[0053] Still referring to FIG. 3, the three LFD components are interconnected wirelessly through a wireless PAN 313. The overall LFD system 300, including the three components, works as a single integrated LFD system. For example, LF content may be streamed from the internet 350 via the interface 315 then processed by a LF processor (LFP) which may be collocated with or as a part of the mobile device 330 to determine the portion of the LF in focus by the viewer and whether it should display it using near-field by the AR LFD component 310 or far-field by the mobile LFD component 330. This can be guided by input provided by a eye-head tracking component of the AR LFD 310 which may be configured to detect, track and predict where the viewer is focused in depth and direction. Once such information is provided to the LFP, it fetches the commensurate LF data segment (if it does not already have it in its local memory) through IP queries to the content server through the cloud. Also, as the LF data segment to be displayed is determined (in location within the mobile LF volume 335), the LFP decides whether that LF segment is near- or far-field and accordingly routes the LF data segment to be displayed to either the AR LFD component 310 (if it is a near-field LF segment) or to the mobile LFD component 330 (if it is a far field LF segment). In both cases, both display components may receive the entire background LF content, in abbreviated format (e.g., lower resolution), to display simultaneously with the viewer in-focus LF segment. The light field display responsible for displaying the viewer in-focus or of-interest LF segment modulates the fully articulated LF content (e.g., fully articulated LF segment 508 shown in FIG. 5) within that LF segment and the other LF components are configured to be displayed as an abbreviated LF background

(e.g., abbreviated LF segment 509 shown in FIG. 5) that supports the viewer gaze search. In one embodiment, any of the three LFD components shown in FIG. 3 are able to display the fully articulated LF viewer in-focus segment including the smart watch display 340.

[0054] The viewer may interact with the displayed LF volume 335 in one of at least two ways: 1) Visual Interaction - Interface Using Eye; and 2) Gesture Interaction - Interface Using Hand.

[0055] 1. Visual Interaction - Interface Using Eye

[0056] With respect to visual interaction, a viewer may scan (or saccade) through the LF volume quickly and the integrated light field display system detects and decides what segment to focus on (similar to the way a viewer does naturally). As soon as the viewer is focused, that LF segment is fully articulated regardless of where it is in the LF volume. A fully articulated LF means a high resolution LF is displayed within the viewer's HVS depth of focus with high resolution adapted to where the in-focus LF segment is located within the LF volume. This means the integrated LF display is able to display high resolution that closely or substantially matches the HVS anywhere within the LF volume. This is a significant advantage because typically in LF displays, resolution degrades the farther the viewer depth of field focus is from the LF modulation surface (see FIGS. 2A and 2B). This capability is made possible because of the distributed nature of the multiple LF display components system which allows the LF display components nearest the viewer's in-focus segment to modulate that LF segment at the highest resolution possible given its closer vicinity to the in-focus segment (see FIG. 2C).

[0057] 2. Gesture Interaction - Interface Using Hand

[0058] The viewer can also interact with the distributed LF volume using his or her hand via a gesture sensor or other suitable gesture sensing device. Augmenting the gesture sensor, which may detect the movement of the hand, palm, thumb and fingers, is a position sensor (micro gyro/accelerometer) that allows the smartwatch within which a gesture sensor may be integrated, to sense the position of the viewer's hand within the LF volume. Together, the hand gesture sensor and the hand position sensor allow/enable the viewer to position his or her hand wherever they want within the distributed LF volume, then issue gesture commands using the hand, wrist, thumb and fingers to interact with objects they view within the LF volume.

[0059] The viewer's interaction with the integrated LF volume is natural in the sense that the viewer first focuses on the LF segment of interest just as they would naturally, then

interacts with the LF using their hand gesture, similar to how they do naturally, to bring objects into their best view position, open and close items or move items or objects from the foreground to the background or vice versa.

[0060] FIG. 4 illustrates an example of the collective light field volume 405 made available to the viewer using the near/far mobile LFD system of FIG. 3. Integrated LF volume 405 includes, for example, AR LF volume 415 displayed by near-eye augmented reality (AR) display 310, mobile LF volume 435 displayed by mobile device 330 and wearable LF volume 445 displayed by wearable device 340. Within each of the display volumes 415, 435, 445 of the three LF components shown in FIG. 4, the optical performance of the LF display in terms of resolution and Modulation Transfer Function (MTF) differ depending on the position of the viewer's eyes shown in FIG. 4 naturally closest to the AR/LF display relative to the modulation surface of the LF display. Typically, the display resolution and MTF would be at its highest value in the vicinity of the LF display modulation surface and falls off systematically with the increase of the viewer's eye distance from the LF display modulation surface (see FIGS. 2A and 2B). This results in the LF optical performance degrading for objects closer to the viewer when the LF modulation surface is farther away from the viewer's eyes (unnaturally, since one would expect an object close to the eye would have higher optical performance).

[0061] As used herein, a fully articulated light field segment (e.g., fully articulated LF segment 508 of FIG. 5) means a light field segment displayed with resolution that closely matches the HVS central foveal region. An abbreviated light field segment (e.g., abbreviated LF segment 509 of FIG. 5) may be displayed with a resolution that closely matches the HVS peripheral region.

[0062] With the collective light field volume shown in FIG. 4, the near/far LF display system is able to select which of the three display components is best-suited, in terms of optical performance MTF, to modulate the LF segment where the viewer is focused. The display function of the overall system is therefore distributed among the three LF display components and the fully-articulated segment of the LF where the viewer is focused is displayed (modulated) by the LF component that provides the highest optical performance in terms of resolution and MTF to the viewer.

[0063] For example, if the viewer is focused on an object that is close to his or her eyes, the AR LFD modulates the fully articulated LF segment incorporating the object the viewer is focused on. On the other hand, if the viewer is focused on an object far from the

eyes, the mobile LFD modulates the fully-articulated segment incorporating the object where the viewer is focused. This way, the objects or depth the viewer is focused on will always be at the highest optical performance whether the viewer is focused in the near or far part of the light field volume (see FIG. 2C).

[0064] An added advantage is that the viewer mobile environment display capabilities are the integrated capabilities of the three LF display components. In this regard, the three LF display components contribute to what is being displayed to the viewer within the LF volume by virtue of the fact that the three LF display components are functionally integrated. The three LF display components, guided by the viewer's interaction using focus and gesture, work together to create a single and cohesive LF display volume 405. Accordingly, the resolution and the volume of the integrated near/far LF display system disclosed herein transcends the capabilities of any one of the three display components standing alone.

[0065] FIG. 5 is an exemplary block diagram illustrating the near/far integrated light field display system of FIG. 3. As illustrated in FIG. 5, the integrated light field display system 500 includes three LF display components, namely the near-eye AR LF display 502 (e.g., 310 of FIG. 3), the mobile LF display 504 (e.g., 330 of FIG. 3), and the smartwatch LF display 505 (e.g., 340 of FIG. 3). The three LF display components are interconnected, for example through a wireless personal area wireless network (WL-PAN) to the light field processor (LFP) 501 which may be collocated within the mobile device 530 together with the mobile LF display component 504.

[0066] Utilizing a mobile wireless wide area network (W- WAN) or local area network (W- LAN) interfaces of the mobile device 530, the LF processor 501 interfaces with the internet 550 for retrieving streaming LF videos and content from a content provider server across the internet 550. The LF processor 501 may incorporate the capability to query the content server interactively to retrieve LF segment just-in-time for display. The LF processor 501 may include the capabilities to decompress, render and re-compress the light field data it receives across the interface to the internet 550 and provide or distribute the appropriate set of LF data to each of the three display components 502, 504, 505 as described earlier.

[0067] As also shown in FIG. 5, a HVS head and eye tracking sensor system 503 is collocated with the AR LF display 502 which may be worn on the viewer's head 507 like a pair of glasses. As previously discussed, head and eye tracking sensor system 503 may determine the direction, depth and focus of the viewer. The HVS sensor output is also relayed

through the AR LF display interface (W-PAN) to the LF processor 501. FIG. 5 also shows the gesture sensor 506 that may be collocated with the smartwatch LF display 505 with its output interfacing to the LF processor 530 through the W-PAN connection between the smartwatch display 505 and the mobile device 530 where the LF processor 501 is collocated.

[0068] These interfaces are all illustrated in FIG. 5 as interconnect lines between the three LF display components and the two sensor components. Functionally, the master frame of reference for the LF display volume 550 is established by the HVS tracking sensor 503 collocated with the AR LF display component 502. The reason is to set the LF display volume reference coordinate to be relative to the position of HVS tracking sensor 503. In one embodiment, all three LF display components 502, 503, 505 have a position sensor and are interconnected through the wireless PAN, such that the relative position of all three LF display components is known to or communicated to the light field processor (LFP) 501 periodically. This can be accomplished using simple triangulation calibration with the viewer initially interacting with the integrated LF display system 500 within preset positions to calibrate the relative positions of the three LF display components and thereafter these position coordinates being updated periodically when the LF processor receives position and orientation updates from all three components of the system.

[0069] FIG. 6 illustrates an example coordinate system that may be used by a light field processor. In particular, FIG. 6 illustrates example coordinates and relative positions of the three components of the integrated light field display, such as the three light field display components of FIG. 3, and illustrates how the relative positions may be triangulated by the light field processor (LFP) primarily to define the integrated LF display volume 335. As illustrated in FIG. 6, once the position of the three display components is calibrated and triangulated by the LF processor, the contribution of each LF display component into the integrated LF display volume 335 (e.g., as shown in FIG. 4) may be established and known to the LFP.

[0070] With the relative position of the three LF display components known and tracked by the LFP, their contribution to the LF display volume is continuously computed and tracked by the LFP. When the viewer focuses on an object or a region within the integrated LF display volume, the LFP computes the position of that object or focus region within the integrated LF display volume then subsequently also computes or estimates the performance metric, for example resolution or MTF, of each LF display component within that focus region, then decides the degree of which, in terms of the level of LF articulation,

each of the three LF display components contribute to displaying the highest quality LF to the viewer whether the focus region is near or far relative to the viewer's HVS frame of reference.

[0071] In doing so, the LFP computes an optical performance metric from each LF display component to the focus region of the viewer. The LFP may also compute the registration of each of the three light field display components to blend the contribution of the three light field display components together and with the ambient light field in color, brightness and geometry seamlessly within the viewer's focus region. In addition, the LFP may also compute a light field color and brightness metric that needs to be satisfied within the viewer's focus region, then adjust the contribution into the focus zone of all the three light field display components' color and brightness in order to achieve the light field uniformity metric within the viewer's zone. In doing so, the LFP may also incorporate the output of an ambient light or scene sensor that may be located or collocated with any of the three LF display components. For example, on either or both of the AR LF display and/or mobile LF display may be a collocated ambient scene sensor such as a camera that may sense the light brightness, color and uniformity (shades and shadows) with the LF display volume. Such sensed ambient light environment (within the LF display volume at large and in particular within the viewer's focus region) may be incorporated by the LFP into the LF display components' LF contribution in order to achieve the target LF uniformity metric. The net result would be presenting to the viewer a unified LF volume modulated by the three LF display components collectively and cooperatively that is seamless within itself and relative to the ambient light field environment in which it is being displayed that is in addition to presenting the viewer with the highest possible optical performance and viewing experience regardless of where in the light field the user is focused.

[0072] In some sense, the three components of the LF display may augment each other and collectively augment the ambient LF to present the viewer with the highest possible performance in viewing experience in viewing the collective light field (collective light field referring to the integrated light field displayed by the multiple components of the LF display system and the ambient LF of the viewer). Similarly, when the viewer interacts with the light field using the gesture features of the LF display system, the LFP may receive the output from the gesture sensor collocated with the smartwatch LF display and worn on the viewer's hand, then locate and use this information to compute the user's hand position within the light field, then compute the position of the viewer's hand, palm, thumb and fingers within the

light field and with respect to the LF contents being displayed. The LFP may then interpret the viewer's hand and thumb/fingers gesture using a preset code of gestures to interact, modify, alter or move the contents of the light field displayed within the integrated light field volume modulated by the three LF display components. The net result is the display of a high quality light field that is cooperatively modulated by the three LF components and interacted with via the viewer's focus and gesture actions relayed by the two sets of sensor integrated with the LF display components.

[0073] Integrated LF Work Station:

[0074] FIG. 7 illustrates an embodiment of an integrated light field display system in a workstation scenario. As depicted in FIG. 7, the near/far light field display system 700 may include three LF components:

[0075] 1. Near eye AR light field display 710 and,

[0076] 2. Multi-panel (e.g., at least two panels or single immersive curve panel) LF display 720.

[0077] The AR LFD 710 may be worn by a workstation user on or near the user's head and may incorporate a head and eye tracking sensor and interface capabilities. In one embodiment, integrated light field display system 700 may also include a wrist worn or handheld gesture sensor with wireless interface capabilities. The light field display elements and the sensor elements may be interconnected via wireless personal area network (WPAN) interface capabilities incorporated as an integral part of each element.

[0078] The multi-panel LF display may be connected to a workstation computer where the light field processor (LFP) 722 may be collocated. As previously mentioned, the AR LFD component 710 may have collocated with it a wireless interface, either W-PAN or W-LAN, and a HVS (head and eye) track sensor. The AR LFD component 710 may also be collocated with an ambient light and/or scene sensor which may be a camera. The LFP 722 may interface wirelessly with the AR LFD component 710. The user or viewer may also wear a hand or wrist band 740 that incorporates a gesture sensor (e.g., a smartwatch).

[0079] In this embodiment, the user/viewer may use a hand-held sensor that allows the sensing of the palm as well as user thumb/finger configuration. The gesture sensor may be hand/wrist wearable to allow free-thumb/finger gesture. The gesture sensor may be able to sense the palm and the user's thumb/finger configuration. A position sensor (micro gyro/accelerometer) may also be integrated with the gesture assembly that senses the position of the user's hand when the gesture sensor is worn. A W-PAN interface device may be

integrated with the gesture assembly to allow the gesture sensor to relay its output to both the LF processor (LFP) as well as the AR LFD if necessary.

[0080] The functionality of the LFP may be very similar to what was previously described herein in connection with other embodiments. In this embodiment, the LFP may interface with the internet or cloud 750 such as through a wireless or wired LAN. Also in this embodiment, since the multi-panel LF display 720 may support a much higher resolution as compared to other displays, the LF processor may have much higher throughput and memory capacity than other embodiments.

[0081] Integrated Head-Up LF Display:

[0082] FIG. 8 illustrates an example of a near/far integrated light field display system in an automotive scenario. As shown in FIG. 8, integrated light field display system 800 may include:

[0083] 1. Automotive LF heads-up light field display (LF HUD) 860; and

[0084] 2. Near-eye augmented reality (AR) light field (LF) display 810.

[0085] The near-eye augmented reality (AR) LFD 810 may be worn by an automobile driver on or near the head. AR LFD 810 may incorporate a head and eye tracking sensor and interface capabilities. The automobile driver may interact with the collective light field volume 825 modulated by the AR and HUD light field display elements 810 and 860 either visually, by gesture or through hands-free voice control.

[0086] The automotive LF HUD 860 may be connected to the LF processor (LFP) 822 through the automobile interconnect system and the LFP 822 may be connected via a wireless PAN to the AR LFD 810. The LFP 822 may also be connected to the internet or cloud 850 through the automotive information system wireless interface 813. The LFP 822 operates in a manner similar to that described herein in connection with other embodiments. For example, LFP 822 may obtain the position of each display element and compute the light field contribution of each display element to the collective light field volume. The light field processor may visually articulate the appropriate portion of the integrated light field based on the viewer's visual and/or gesture cues to modulate that light field segment at the highest possible optical performance.

[0087] The integrated light field display system 800 may also include a wrist-worn or handheld gesture sensor with wireless interface capabilities. The light field elements and the sensor elements may be interconnected via a wireless personal area network (W-PAN) interface capabilities incorporated as an integral part of each element.

[0088] Integrated Home Entertainment LF Display:

[0089] FIG. 9 illustrates an example of an integrated light field display system in home entertainment scenario. As depicted in FIG. 9, an integrated light field display system 900 may include:

[0090] 1. Direct view home entertainment light field display 920; and

[0091] 2. Multiplicity of near-eye AR LF displays 910 (individually, 910A, 910B, 910C).

[0092] FIG. 9 illustrates the integrated light field display system 900 being comprised of a plurality of near-eye augmented reality (AR) light field displays 910 worn by multiple viewers and a direct view light field home entertainment display 920. Each of the AR LFD elements 910 may be worn on or near the head of a viewer and may incorporate a head and eye tracking sensor and wireless interface capabilities. The viewers may interact with the collective light field volume 905 modulated by the integrated light field display system 900 either visually, or through a wrist-worn or handheld gesture sensor incorporating wireless interface capabilities. The integrated light field display system 900 may include an LFP 922 in communication with the internet or cloud 950. The LFP 922 operates in a manner similar to that described herein in connection with other embodiments. For example, LF processor 922 may obtain the position of each display element and compute the light field contribution of each display element to the collective light field volume. The LFP 922 may visually articulate the appropriate portion of the integrated light field based on the viewers' visual and/or gesture cues to modulate that light field segment at the highest possible optical performance.

[0093] Integrated Cinema and Large Venue LF Display:

[0094] FIG. 10 illustrates an example of the integrated light field display in a cinematic entertainment scenario. As depicted in FIG. 10, an integrated light field display system 1000 may include:

[0095] 1. Direct-view large venue LF display 1020; and

[0096] 2. Multiplicity of near-eye AR LF displays 1010 (individually, 1010A-1010N).

[0097] FIG. 10 illustrates integrated light field display system 1000 comprised of a plurality of near-eye augmented reality (AR) Light Field Displays 1010 worn by multiple viewers and a direct-view Light Field Display 1020 being viewed by the multiple viewers. Each of the AR light field display elements 1010 may be worn on or near a head of the viewer

and may incorporate a head and eye tracking sensor and wireless interface capabilities. The integrated light field display system 1000 may include an LF processor (LFP) 1022 coupled to the internet or cloud 1050, or to a local server. The LF processor 1022 operates in a manner similar to that described herein in connection with other embodiments. For example, LF processor 1022 may obtain the position of each display element and compute the light field contribution of each display element to the collective light field volume. The light field processor may visually articulate the appropriate portion of the integrated light field based on the viewer's visual and/or gesture cues to modulate that light field segment at the highest possible optical performance.

[0098] The viewers may interact with the collective light field volume 1005 modulated by the integrated light field display system 1000 visually. Such visual interaction (e.g., through focus by individual viewers) allows each viewer to independently focus on objects of their interest within the LF display volume 1005 to experience a personal close-in viewing experience.

[0099] The integrated LF display context illustrated in FIG. 10 may also be a concert or theater hall with the audience being communicatively coupled (e.g., via wireless connection 1013) to the LF processor 1022 to receive multiple perspectives of the LF captured by multiple cameras of the concert or theatrical play being performed. Such multiple perspectives of the concert or theatrical play may be captured by multiple cameras having different perspectives of the stage. The multiple cameras may be communicatively coupled (connected either by wire or wirelessly) to the LF processor to provide real-time LF capture of the performance on the stage. The viewers may interact with the collective light field volume 1005 modulated by the integrated light field display system 1000 visually by focusing on region or objects on the stage performance or what is being displayed on a large venue LF display 1020 displaying the captured LF of the stage performance. Such visual interaction (through focus by individual viewers) allows each viewer to independently focus on objects of their interest within the LF display volume 1005 to experience a personal close-in viewing experience the stage entertainment being performed on the stage.

[0100] The integrated LF display context illustrated in FIG. 10 could also be a sports arena or stadium venue with the audience being communicatively coupled (e.g., connected wirelessly) to the LFP 1022 to receive multiple perspectives of the LF captured by multiple cameras of the sport event or theatrical play being performed. Such multiple perspectives of the sport event may be captured by multiple cameras having different perspectives of the

sport arena or the field of the stadium. The multiple cameras may be communicatively coupled (e.g., connected either by wire or wirelessly) to the LFP 1022 to provide real-time LF capture of the game being played. The viewers may interact with the collective light field volume 1005 modulated by the integrated light field display system 1000 visually by focusing on a region or objects on the sport area or the field of the stadium or what is being displayed on a large venue LF display 1020 displaying the captured LF on one or more direct view large venue LF displays being visually accessible to the spectators. Such visual interaction (through focus by individual viewers) allows each of the spectators to independently focus on objects of their interest within the LF display volume to experience a personal, close-in viewing experience of the sport event.

[0101] The embodiment of FIG. 10 therefore provides a light field that is personally focusable by a viewer, as well as visual interaction for a personal close-in focus experience.

[0102] Integrated Light Field General Use Scenario:

[0103] A general use scenario of the integrated light field display system of the invention encompasses a multiplicity of the aforementioned embodiments whereby the AR LFD typically used by (mobile) users is compatible with (or can support) the described interface and cooperative (or distributed) processing of the integrated LFD system as well as the typical visual interface devices, e.g., the mobile device, the HUD, workstation, the home entertainment system, commercial venues display, etc., encountered by the AR LFD users in their typical daily activities. This enables the users of the integrated LFD compatible AR LFD to seamlessly integrate visually with a virtual light field environment of any of the integrated LFD compatible visual devices they encounter in their daily activities in order to enable richer visual light field experience for the users of the AR LFD.

[0104] Many alterations and modifications may be made by those having ordinary skill in the art without departing from the spirit and scope of the disclosure. Therefore, it must be understood that the illustrated embodiment has been set forth only for the purposes of example and that it should not be taken as limiting the disclosure as defined by any claims in any subsequent application claiming priority to this application.

[0105] For example, notwithstanding the fact that the elements of such a claim may be set forth in a certain combination, it must be expressly understood that the disclosure includes other combinations of fewer, more or different elements, which are disclosed in above even when not initially claimed in such combinations.

[0106] The words used in this specification to describe the disclosure and its various embodiments are to be understood not only in the sense of their commonly defined meanings, but to include by special definition in this specification structure, material or acts beyond the scope of the commonly defined meanings. Thus, if an element can be understood in the context of this specification as including more than one meaning, then its use in a subsequent claim must be understood as being generic to all possible meanings supported by the specification and by the word itself.

[0107] The definitions of the words or elements of any claims in any subsequent application claiming priority to this application should be, therefore, defined to include not only the combination of elements which are literally set forth, but all equivalent structure, material or acts for performing substantially the same function in substantially the same way to obtain substantially the same result. In this sense, it is therefore contemplated that an equivalent substitution of two or more elements may be made for any one of the elements in such claims below or that a single element may be substituted for two or more elements in such a claim.

[0108] Although elements may be described above as acting in certain combinations and even subsequently claimed as such, it is to be expressly understood that one or more elements from a claimed combination can in some cases be excised from the combination and that such claimed combination may be directed to a subcombination or variation of a subcombination.

[0109] Insubstantial changes from any subsequently claimed subject matter as viewed by a person with ordinary skill in the art, now known or later devised, are expressly contemplated as being equivalently within the scope of such claims. Therefore, obvious substitutions now or later known to one with ordinary skill in the art are defined to be within the scope of the defined elements.

[0110] Any claims in any subsequent application claiming priority to this application are thus to be understood to include what is specifically illustrated and described above, what is conceptually equivalent, what can be obviously substituted and also what essentially incorporates the essential idea of the disclosure.

CLAIMS

What is claimed is:

1. An integrated light field display system comprising:
a first light field display element configured to display a near-field light field segment of a collective light field volume, the collective light field volume comprising a predetermined set of optical performance light field characteristics;
a second light field display element configured to display a far-field light field segment of the collective light field volume; and
a light field processor communicatively coupled to the first and second light field display elements and configured to:
determine, within the collective light field volume, a three-dimensional position of the first light field display element and a three-dimensional position of the second light field display element,
determine, based on which light field segment is focused on by a viewer, a modulation transfer function of the first light field display element and a modulation transfer function of the second light field display element; and
modulate at least one of the near-field and far-field light field segments based on at least one of the determined modulation transfer functions.
2. The integrated light field display system of claim 1 wherein the first light field display element comprises a near-eye wearable optical see-through glasses device.
3. The integrated light field display system of claim 1 wherein the first light field display element comprises a near-eye wearable optical see-through glasses device configured to operate as an augmented reality display.
4. The integrated light field display system of claim 1 wherein the first light field display element comprises at least one of a visual or location sensor configured to localize the viewer within the collective light field volume.

5. The integrated light field display system of claim 1 wherein the first light field display element is further configured to include a simultaneous localization and mapping capability that localizes the viewer within the collective light field volume.

6. The integrated light field display system of claim 1 wherein the first light field display element comprises at least one of a viewer eye-gaze tracking sensor, an inter-pupillary distance sensor and a head orientation sensor configured for determining a location of a viewer's focus within the collective light field volume.

7. The integrated light field display system of claim 6 further comprising a gesture control device configured to enable the viewer to interact with the collective light field volume.

8. The integrated light field display system of claim 1 wherein the second display element is communicatively coupled to the first display element.

9. The integrated light field display system of claim 1 wherein the integrated light field display system is communicatively coupled to an external content source and is configured to receive from the external content source streaming light field display content for display in the collective light field volume.

10. The integrated light field display system of claim 1 wherein the first light field display element is further configured to operate at a first light field display resolution, wherein the second display element is configured to operate at a second light field display resolution that is lower than the first light field display resolution, and wherein the first light field display resolution is complementary to the second light field display resolution.

11. The integrated light field display system of claim 1 wherein the first light field display element is further configured to operate at a first light field display resolution, wherein the second display element is configured to operate at a second light field display resolution that is higher than the first light field display resolution,

and wherein the second light field display resolution is complementary to the first light field display resolution.

12. The integrated light field display system of claim 1 wherein a plurality of views of the collective light field volume being modulated by the second light field display element are dynamically adjusted to correspond to a number and a location of each of a plurality of viewers engaging the integrated light field display system.

13. The integrated light field display system of claim 1 wherein the collective light field volume is modulated at a first angular resolution by the second light field display element, and wherein in response to a viewer depth or a vergence being detected, an object in the collective light field volume is brought into a second angular resolution that is higher than the first angular resolution by the first light field display element.

14. The integrated light field display system of claim 1 wherein the collective light field volume is angularly partitioned.

15. The integrated light field display system of claim 1 wherein the collective light field volume is volumetrically partitioned.

16. The integrated light field display system of claim 1 wherein the first light field display element comprises a wearable near-eye augmented reality device and the second light field display element comprises a mobile phone device including a light field display.

17. The integrated light field display system of claim 16 further comprising a gesture control element configured to enable the viewer to interact with the collective light field volume.

18. The integrated light field display system of claim 17 wherein the gesture control element comprises a light field display element and is

communicatively coupled with the first and second light field display elements and the light field processor.

19. The integrated light field display system of claim 18 wherein the light field processor is configured to determine and adjust a contribution of a color and a brightness of each of the first and second light field display elements and the light field display element of the gesture control element to a focus zone of the viewer.

20. The integrated light field display system of claim 1 wherein the second light field display element comprises a head-up light field display.

21. The integrated light field display system of claim 1 wherein the first light field display element is a wearable near-eye augmented reality device and the second light field display element is comprised of a multi-panel light field display.

22. A method for integrated light field display, the method comprising:
displaying a near-field light field segment of a collective light field volume, the collective light field volume comprising a predetermined set of optical performance light field characteristics;

displaying a far-field light field segment of the collective light field volume;

determining, within the collective light field volume, a three-dimensional position of the first light field display element and a three-dimensional position of the second light field display element,

determining, based on which light field segment is focused on by a viewer, a modulation transfer function of the first light field display element and a modulation transfer function of the second light field display element; and

modulating at least one of the near-field and far-field light field segments based on at least one of the determined modulation transfer functions.

23. The method of claim 22 further comprising determining coordinates of a location of the viewer within the collective light field volume.

24. The method of claim 22 further comprising receiving at least one of viewer eye-gaze tracking information, interpupillary distance information and head orientation information for determining a location of a viewer's focus within the collective light field volume.

25. The method of claim 22 further comprising receiving gesture control information to enable the viewer to interact with the collective light field volume.

26. The method of claim 22 further comprising receiving from an external content source streaming light field display content for display in the collective light field volume.

27. The method of claim 22 wherein the near-field light field segment is displayed at a first light field display resolution, wherein the far-field light field segment is displayed a second light field display resolution that is lower than the first light field display resolution, and wherein the first light field display resolution is complementary to the second light field display resolution.

28. The method of claim 22 wherein the near-field light field segment is displayed at a first light field display resolution, wherein the far-field light field segment is displayed at a second light field display resolution that is higher than the first light field display resolution, and wherein the second light field display resolution is complementary to the first light field display resolution.

29. The method of claim 22 wherein a plurality of views of the collective light field volume being modulated with respect to the far-field light field segment are dynamically adjusted to correspond to a number and a location of each of a plurality of viewers engaging with integrated light field display.

30. The method of claim 22 wherein the collective light field volume is modulated at a first angular resolution with respect to the far-field light segment, and wherein in response to a viewer depth or a vergence being detected, an object in the

collective light field volume is brought into a second angular resolution that is higher than the first angular resolution with respect to the near-field light segment.

31. The method of claim 22 wherein the collective light field volume is angularly partitioned.

32. The method of claim 22 wherein the collective light field volume is volumetrically partitioned.

33. The method of claim 22 further comprising determining and adjusting a contribution of a color and a brightness of each of the near-field light field segment and the far-field light field segment to a focus zone of the viewer.

34. A non-transitory machine-readable medium having instructions stored thereon, which when executed by a processor, cause the processor to perform the following method for integrated light field display, the method comprising:

displaying a near-field light field segment of a collective light field volume, the collective light field volume comprising a predetermined set of optical performance light field characteristics;

displaying display a far-field light field segment of the collective light field volume;

determining, within the collective light field volume, a three-dimensional position of the first light field display element and a three-dimensional position of the second light field display element,

determining, based on which light field segment is focused on by a viewer, a modulation transfer function of the first light field display element and a modulation transfer function of the second light field display element; and

modulating at least one of the near-field and far-field light field segments based on at least one of the determined modulation transfer functions.

35. The non-transitory machine-readable medium of claim 34, wherein the method further comprises determining coordinates of a location of the viewer within the collective light field volume.

36. The non-transitory machine-readable medium of claim 34, wherein the method further comprises receiving at least one of viewer eye-gaze tracking information, interpupillary distance information and head orientation information for determining a location of a viewer's focus within the collective light field volume.

37. The non-transitory machine-readable medium of claim 34, wherein the method further comprises receiving gesture control information to enable the viewer to interact with the collective light field volume.

38. The non-transitory machine-readable medium of claim 34, wherein the method further comprises receiving from an external content source streaming light field display content for display in the collective light field volume.

39. The non-transitory machine-readable medium of claim 34, wherein the near-field light field segment is displayed at a first light field display resolution, wherein the far-field light field segment is displayed at a second light field display resolution that is lower than the first light field display resolution, and wherein the first light field display resolution is complementary to the second light field display resolution.

40. The non-transitory machine-readable medium of claim 34, wherein the near-field light field segment is displayed at a first light field display resolution, wherein the far-field light field segment is displayed at a second light field display resolution that is higher than the first light field display resolution, and wherein the second light field display resolution is complementary to the first light field display resolution.

41. The non-transitory machine-readable medium of claim 34, wherein a plurality of views of the collective light field volume being modulated with respect to the far-field light field segment are dynamically adjusted to correspond to a number and a location of each of a plurality of viewers engaging with integrated light field display.

42. The non-transitory machine-readable medium of claim 34, wherein the collective light field volume is modulated at a first angular resolution with respect to the far-field light segment, and wherein in response to a viewer depth or a vergence being detected, an object in the collective light field volume is brought into a second angular resolution that is higher than the first angular resolution with respect to the near-field light segment.

43. The non-transitory machine-readable medium of claim 34, wherein the collective light field volume is angularly partitioned.

44. The non-transitory machine-readable medium of claim 34, wherein the collective light field volume is volumetrically partitioned.

45. The non-transitory machine-readable medium of claim 34, wherein the method further comprises determining and adjusting a contribution of a color and a brightness of each of the near-field light field segment and the far-field light field segment to a focus zone of the viewer.

46. A method for integrated light field display using a light field processor, the method comprising:

- receiving visual interaction information from a first light field display element worn by a viewer;
- receiving position and orientation information from the first light field display element and a second light field display element;
- computing three-dimensional coordinates indicating the position and the orientation of the first and second light field display elements based on the received position and orientation information;
- computing a light field contribution of each of the first and second light display elements to a collective light field volume using the coordinates indicating the position and the orientation of the first and second light field display elements, wherein the collective light field volume comprises a predetermined set of optical performance light field characteristics;

determining a portion of the collective light field volume on which the viewer is focused based on the received visual interaction information;

determining whether the portion of the collective light field volume on which the user is focused should be displayed by the first light field display element or the second light field display element based on the visual interaction information and the coordinates indicating the position and orientation of the first and second light field display elements; and

providing light field data for the portion of the collective light field volume on which the user is focused to the first light field display element or the second light field display element based on the determination of whether the portion should be displayed by the first light field display element or the second light field display element.

47. The method of claim 46 wherein the visual interaction is determined by receiving head and eye tracking information from the first light field display element worn by the viewer.

48. The method of claim 46 further comprising, based on the portion of the collective light field volume on which the user is focused, determining a modulation transfer function of the first light field display element and a modulation transfer function of the second light field display element, wherein the determination of whether the portion of the collective light field volume on which the user is focused should be displayed by the first light field display element or the second light field display element is based on at least one of the modulation transfer functions.

49. The method of claim 46 further comprising receiving gesture information to enable the viewer to interact with the collective light field volume, wherein determining the portion of the collective light field volume on which the viewer is focused is based on the gesture information, and wherein determining whether the portion of the collective light field volume on which the viewer is focused should be displayed by the first light field display element or the second light field display element is based on the gesture information.

50. The method of claim 46 wherein if the light field data for the portion of the collective light field volume on which the user is focused is provided to the first light field display element, light field data for a background portion of the collective light field volume is provided to the second light field display element in an abbreviated format.

51. The method of claim 47 wherein if the light field data for the portion of the collective light field volume on which the user is focused is provided to the second light field display element, light field data for a background portion of the collective light field volume is provided to the first light field display element in an abbreviated format.

52. A light field processor included in an integrated light field display system, the light field processor comprising:

- a communication interface for receiving visual interaction information from a first light field display element worn by a viewer and receiving position and orientation information from the first light field display element and a second light field display element;

- one or more processors;

- one or more memory devices coupled to the one or more processors, the one or more memory devices storing instructions that cause the one or more processors to perform operations including:

- computing three-dimensional coordinates indicating the position and the orientation of the first and second light field display elements based on the received position and orientation information;

- computing a light field contribution of each of the first and second light display elements to a collective light field volume using the coordinates indicating the position and the orientation of the first and second light field display elements, wherein the collective light field volume comprises a predetermined set of optical performance light field characteristics;

- determining a portion of the collective light field volume on which the viewer is focused based on the received visual interaction information;

determining whether the portion of the collective light field volume on which the user is focused should be displayed by the first light field display element or the second light field display element based on the visual interaction information and the coordinates indicating the position and orientation of the first and second light field display elements; and

providing light field data for the portion of the collective light field volume on which the user is focused to the first light field display element or the second light field display element based on the determination of whether the portion should be displayed by the first light field display element or the second light field display element.

53. A non-transitory machine-readable medium having instructions stored thereon, which when executed by a processor, cause the processor to perform the following method for integrated light field display, the method comprising:

receiving visual interaction information from a first light field display element worn by a viewer;

receiving position and orientation information from the first light field display element and a second light field display element;

computing three-dimensional coordinates indicating the position and the orientation of the first and second light field display elements based on the received position and orientation information;

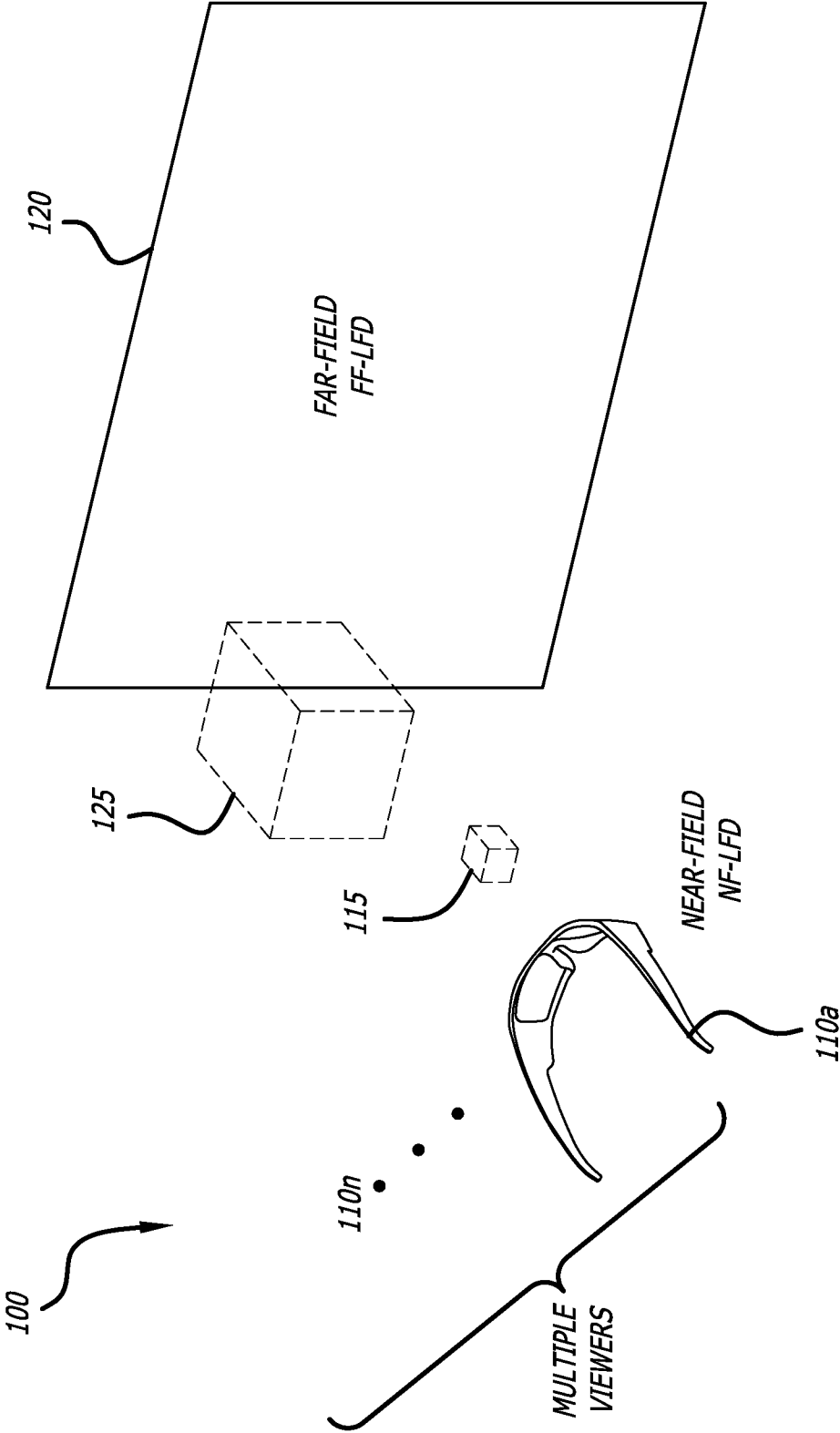
computing a light field contribution of each of the first and second light display elements to a collective light field volume using the coordinates indicating the position and the orientation of the first and second light field display elements, wherein the collective light field volume comprises a predetermined set of optical performance light field characteristics;

determining a portion of the collective light field volume on which the viewer is focused based on the received visual interaction information;

determining whether the portion of the collective light field volume on which the user is focused should be displayed by the first light field display element or the second light field display element based on the visual interaction information and the coordinates indicating the position and orientation of the first and second light field display elements; and

providing light field data for the portion of the collective light field volume on which the user is focused to the first light field display element or the second light field display element based on the determination of whether the portion should be displayed by the first light field display element or the second light field display element.

FIG. 1



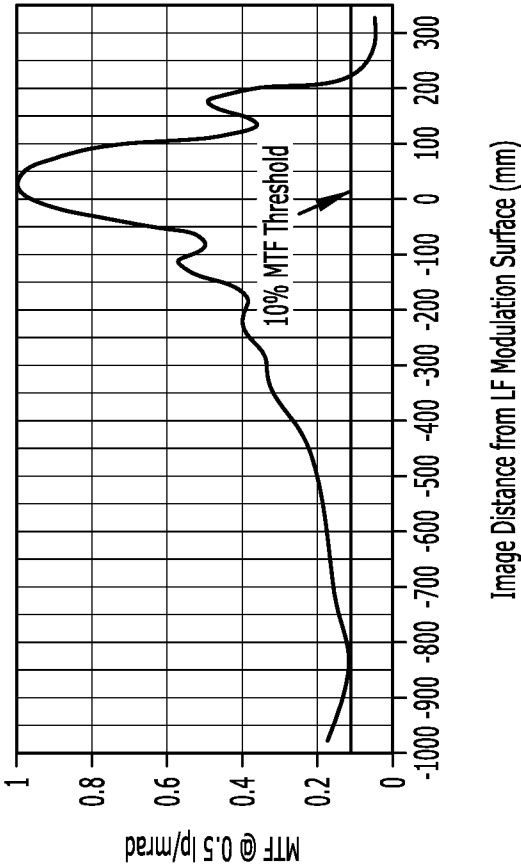


FIG. 2B

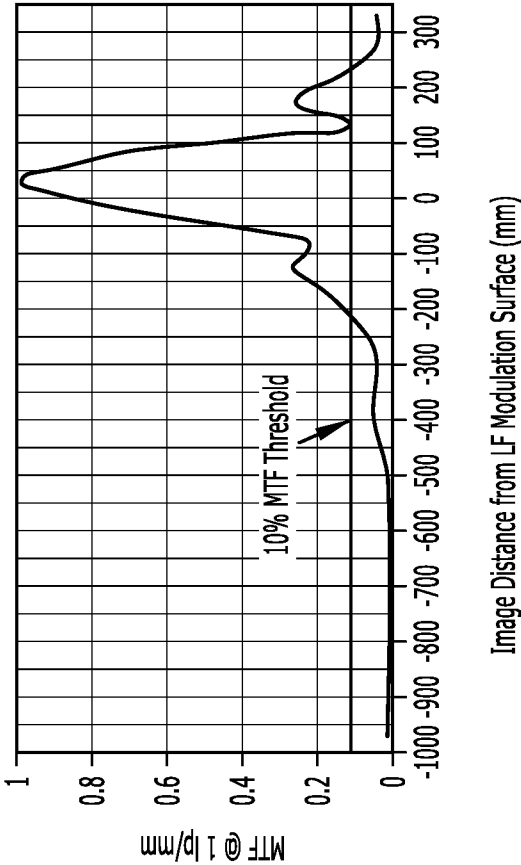


FIG. 2A

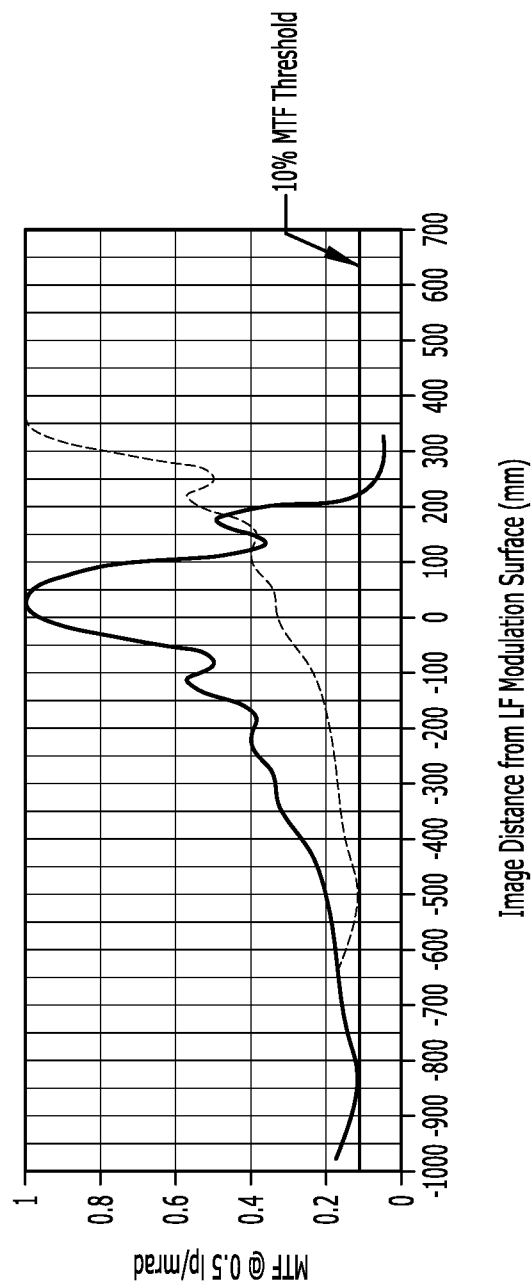
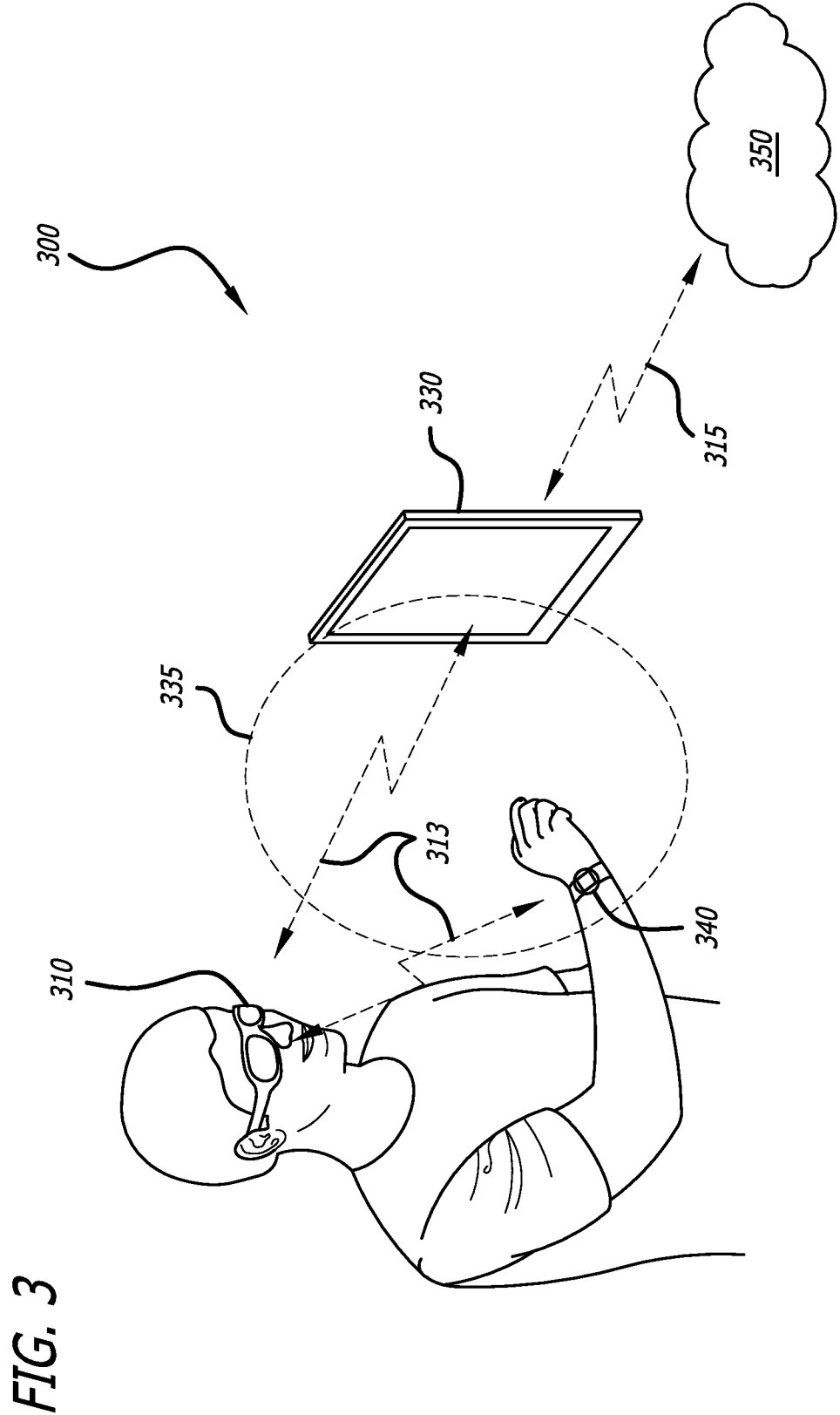


FIG. 2C



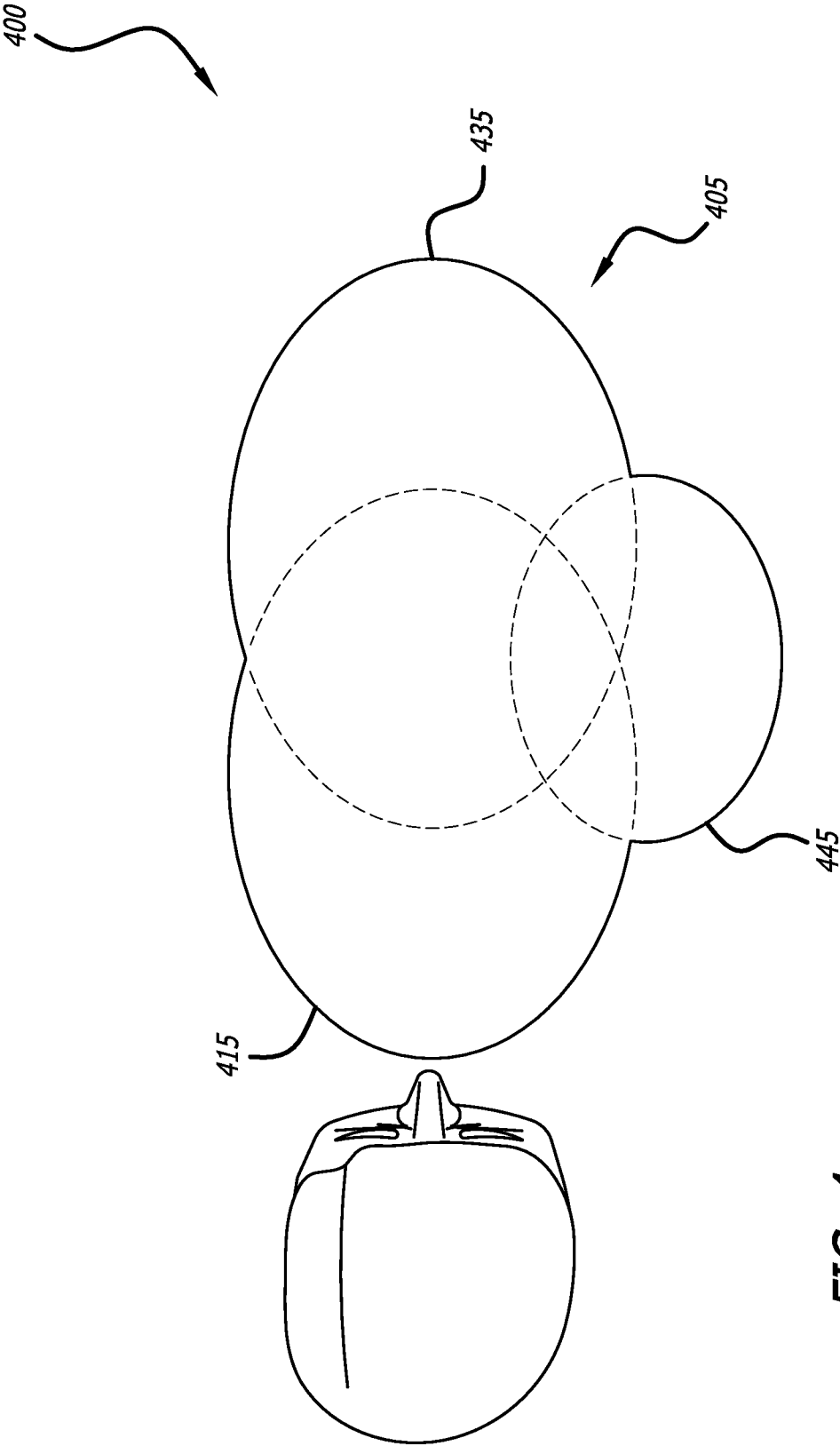


FIG. 4

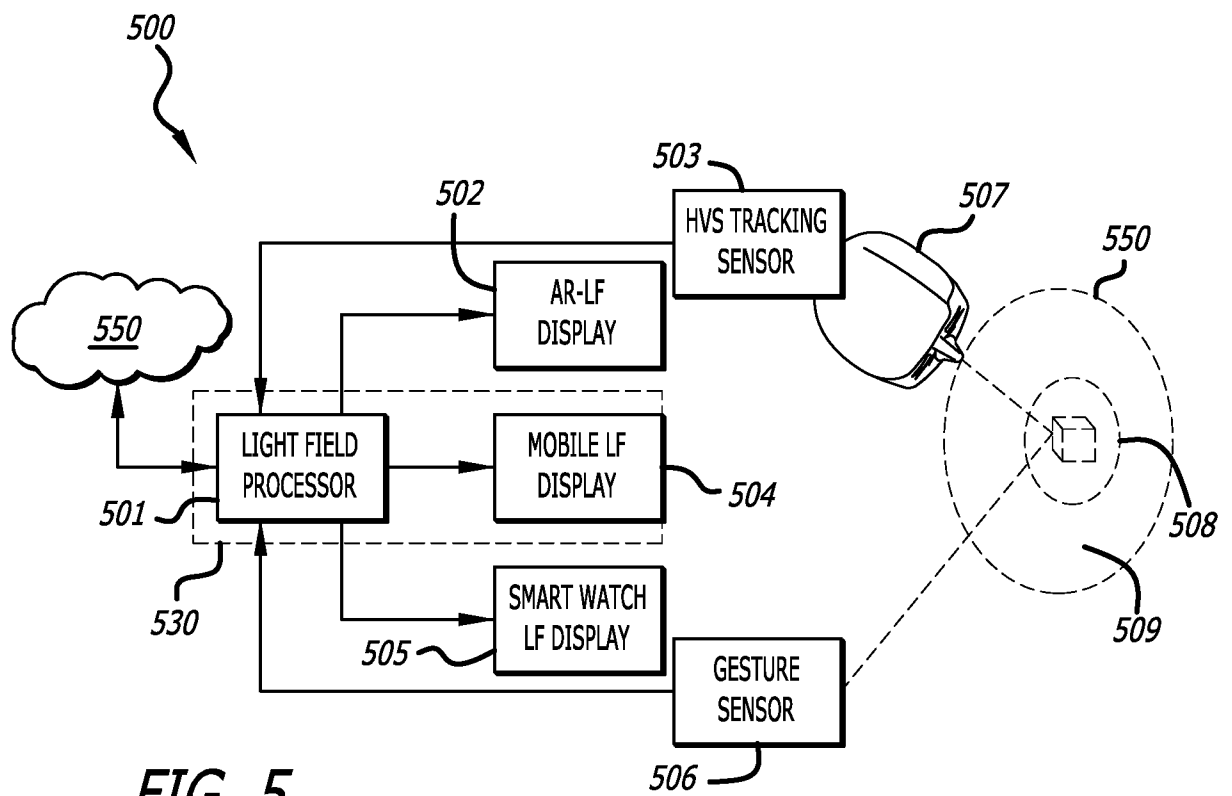


FIG. 5

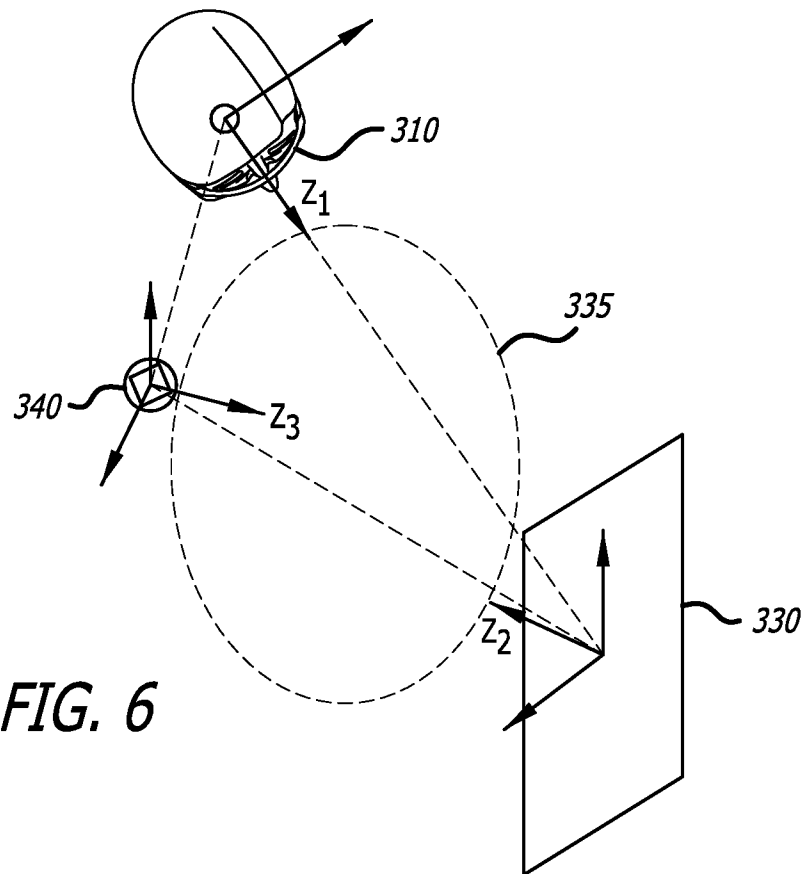


FIG. 6

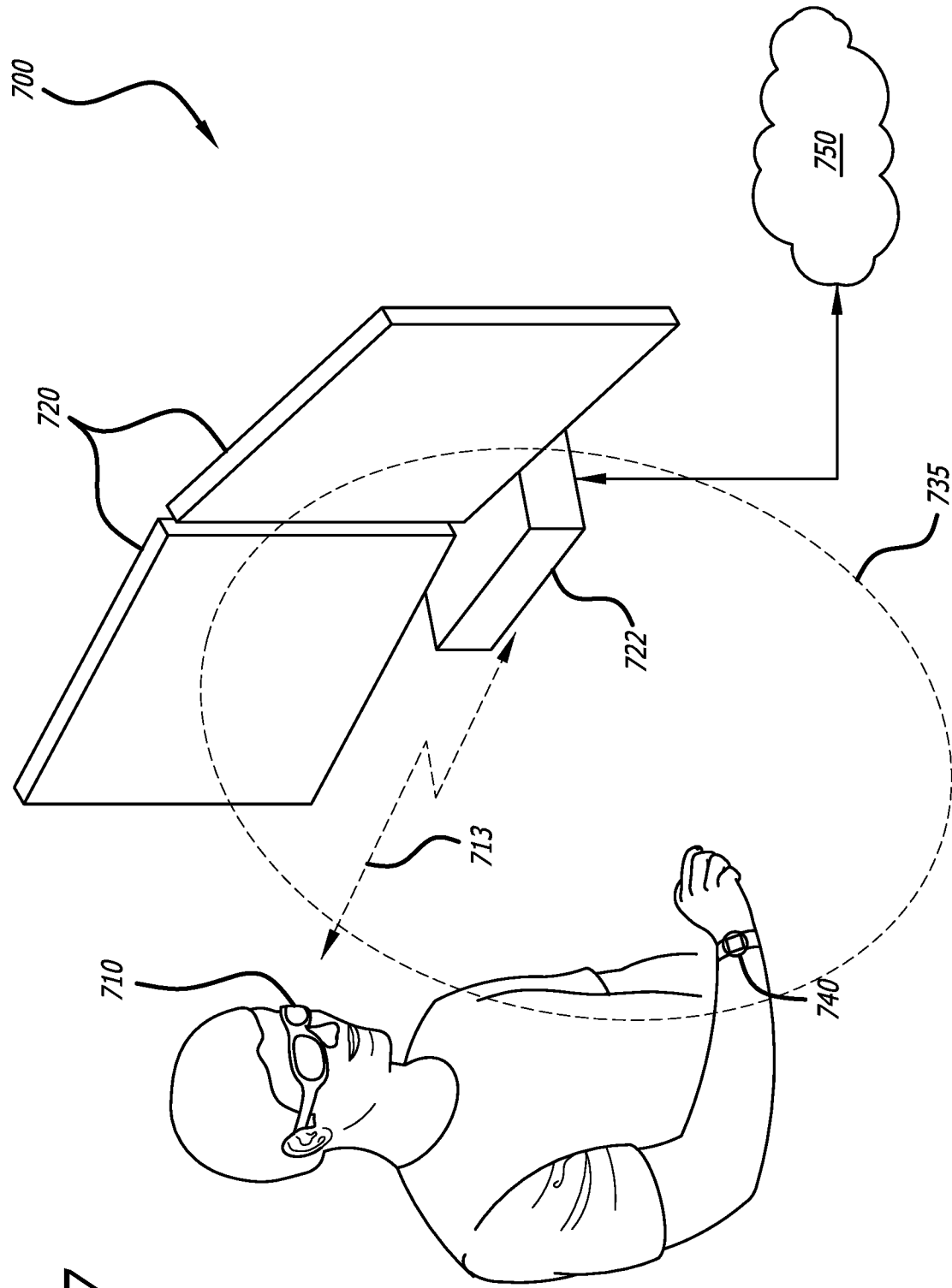
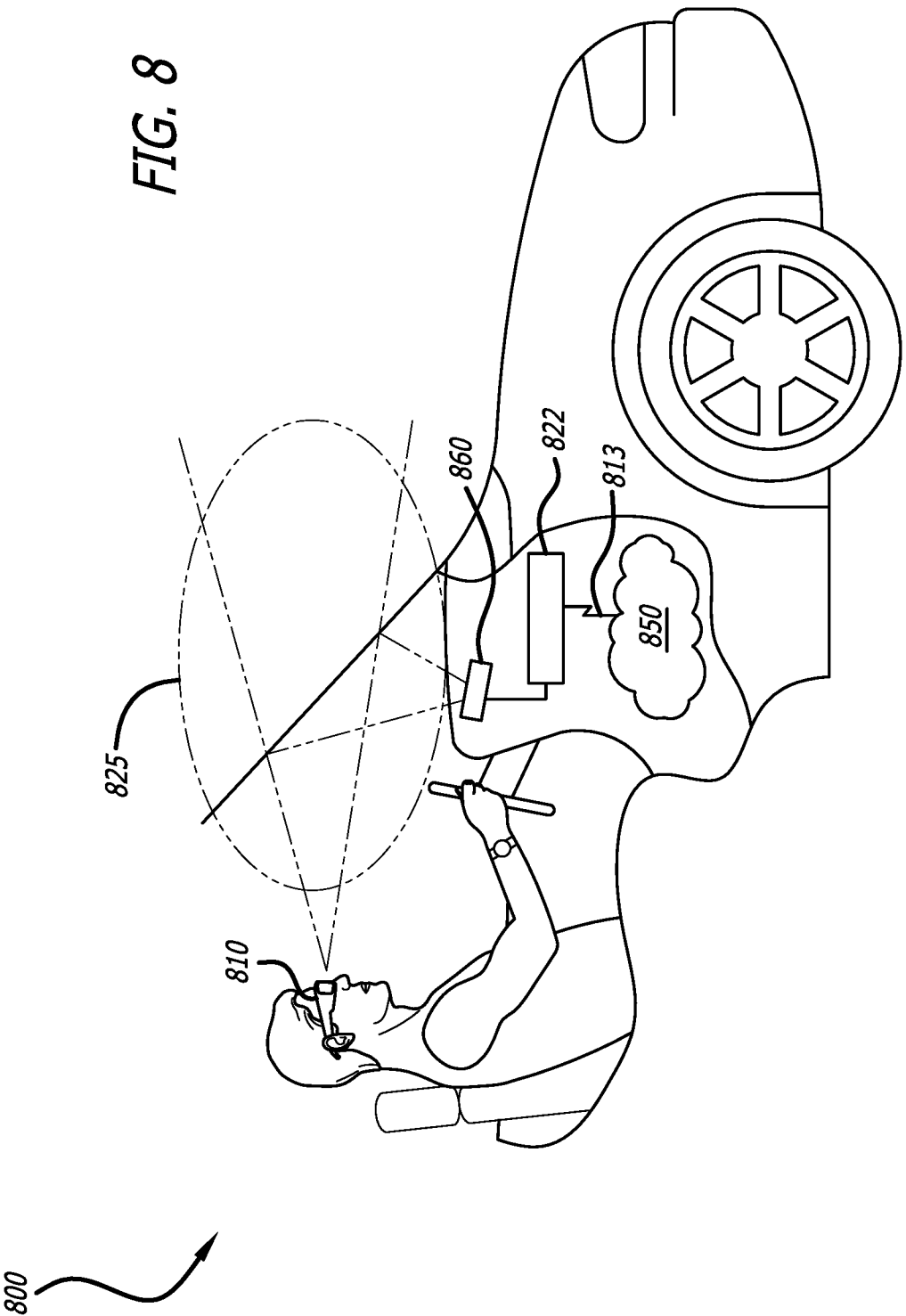
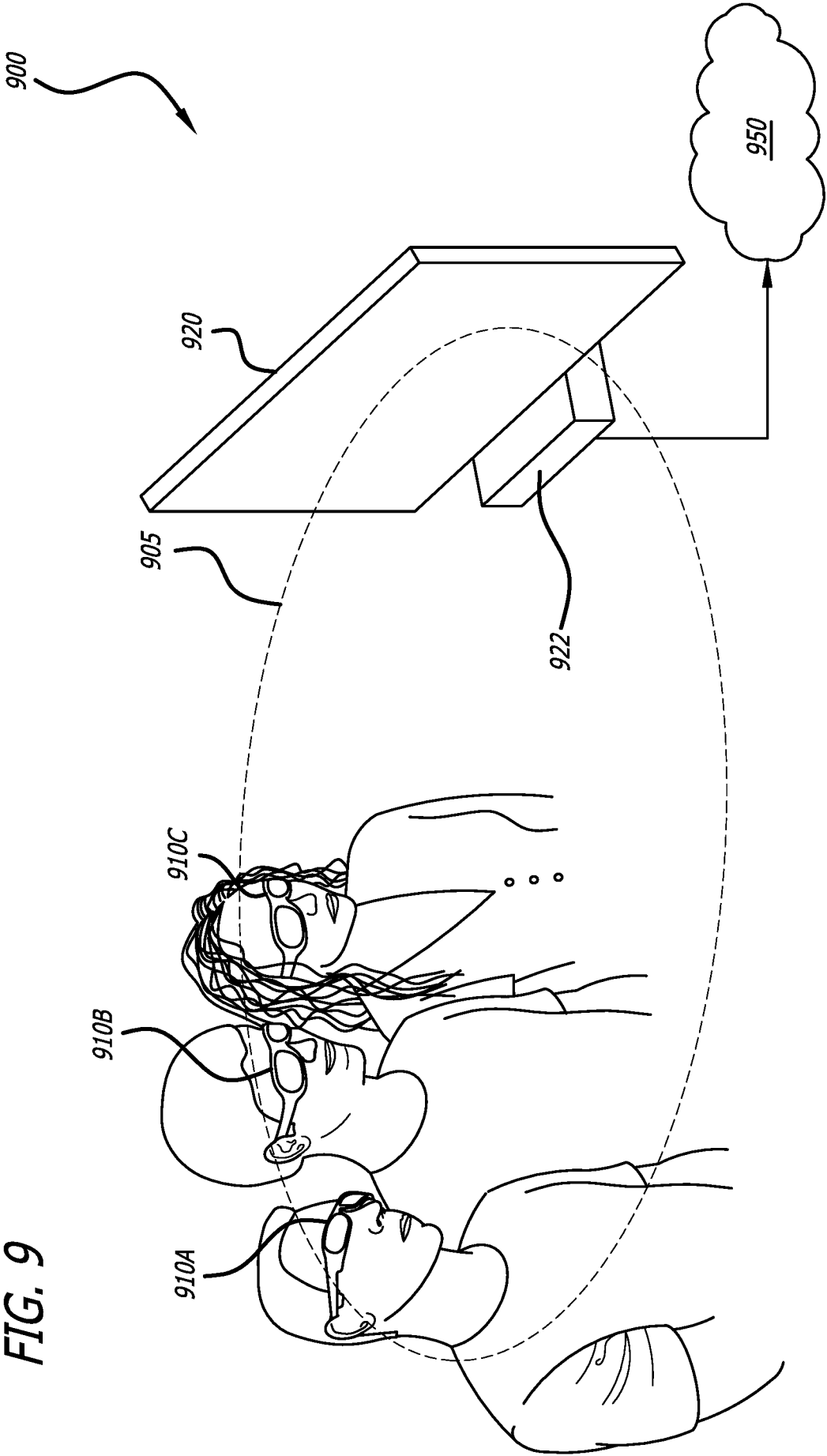
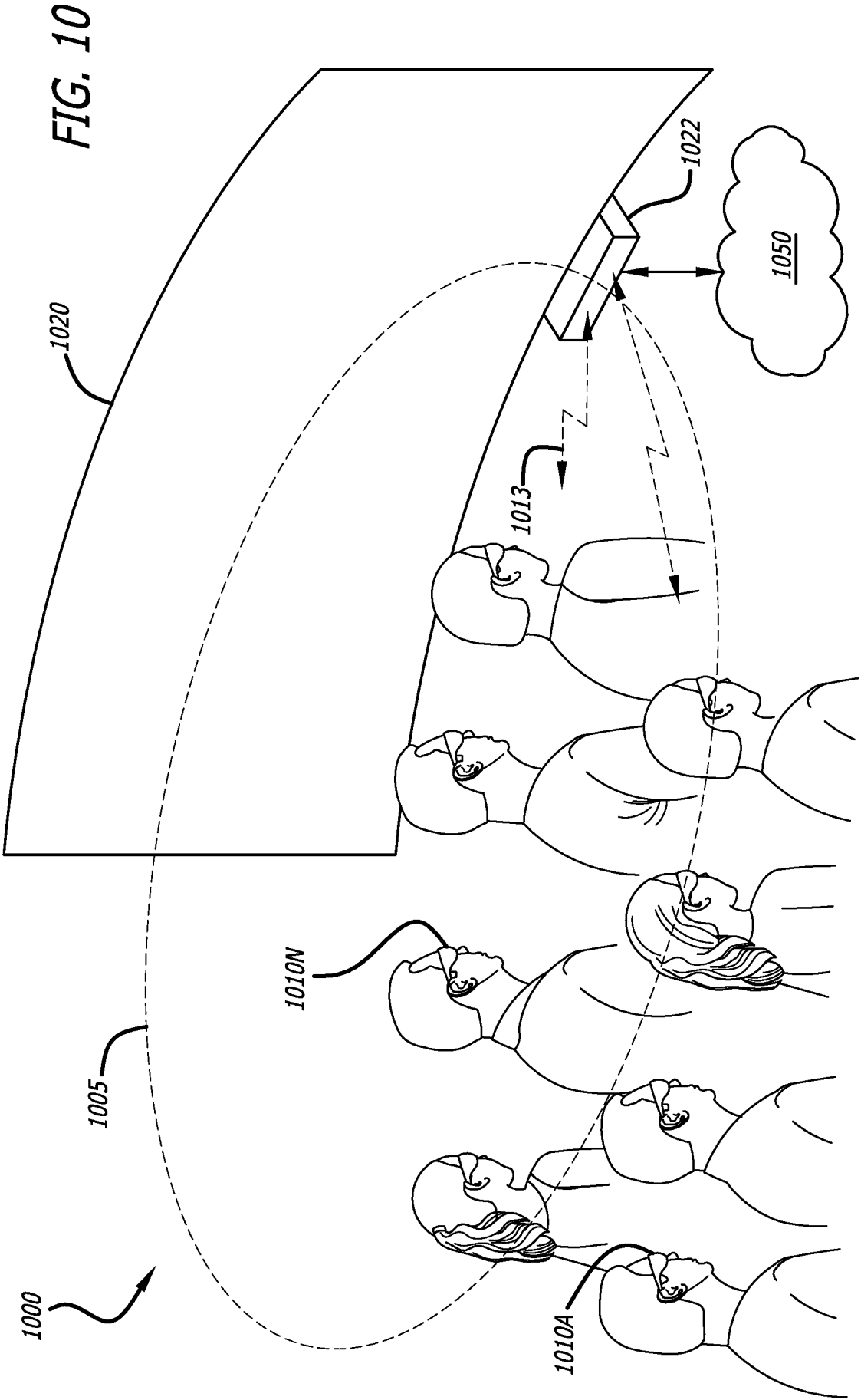


FIG. 7







INTERNATIONAL SEARCH REPORT

International application No.

PCT/US20 17/030280

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H04N 13/04; G06F 3/00; G06F 3/01 ; G09G 5/1 2; G09G 5/1 4 (201 7.01)

CPC - H04N 13/0436; G06F 3/01 3; G06F 3/01 7; G09G 5/1 2; G09G 5/1 4; H04N 13/0429; H04N 13/0447 (201 7.02)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

USPC - 345/6; 345/7; 345/8; 345/9; 345/2.3; 348/78 (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2014/0292620 A 1 (LAPSTUN) 02 October 2014 (02.10.2014) entire document	1-53
Y	US 2012/0105310 A 1 (SVERDRUP et al) 03 May 2012 (03.05.2012) entire document	1-53
Y	US 2014/0168062 A 1 (AFFIAS et al) 19 June 2014 (19.06.2014) entire document	7, 17-19, 25, 37, 49
A	US 2013/0286053 A 1 (FLECK et al) 31 October 2013 (31.10.2013) entire document	1-53
A	US 2013/0286178 A 1 (LEWIS et al) 31 October 2013 (31.10.2013) entire document	1-53

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"G" document member of the same patent family

Date of the actual completion of the international search

27 June 2017

Date of mailing of the international search report

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Name and mailing address of the ISA/US

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