Volumetric Imaging with Mirrors: A Practical Solution to the Vergence Accommodation Conflict (VAC)

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Augmented Reality and Virtual Reality glasses typically cause eyestrain, eye fatigue, and nausea if worn for more than a few minutes. The reasons for this discomfort have been well researched and documented, [1, 2], but effective solutions remain elusive. The problem, commonly referred to as the Vergence Accommodation Conflict (VAC) is an optically induced problem caused by lens-based optics. Humans do not experience the VAC when looking at the real world. The VAC is the disparity between the fixed focal distance of lens-based optic systems and the generated imagery.

Lens-Based Optics

Lens-based optics produce planar wavefronts. Planar wavefronts do not provide the necessary mono and stereo cues for proper depth perception.

The purpose of this paper is to provide an alternative approach that uses multiple off-axis curved first-surface Mirror-Based optics to generate Volumetric Imagery. This technique generates freeform wavefronts which provide the necessary mono and stereo cues the visual cortex requires to determine proper depth, this eliminates the Vergence/Accommodation conflict (VAC).

Almost all Near-To-Eye (NTE) systems today use some form of lenses to create their imagery. They are designed to see the world as a camera-lens sees the world, by focusing to an image plane. In the real world, there is no such thing as an image plane; this is a manmade contrivance and is the biggest limiting factor with current AR/VR/MR/XR hardware optical strategy. The world as we perceive it is four dimensional volume; X,Y,Z + Time.

It is the fixed distance; planar imaging that causes the Vergence/Accommodation Conflict, (VAC) resulting in eye strain and eye fatigue. Lens-based optics can be thought of as a compression of a source volumetric image into a flat virtual image that is lacking proper mono and stereo information. The resulting planar wavefront produces an image that is perceived as unnatural and uncomfortable and is only in focus at one distance. There is no (or very little) depth of field to the image. Changing the distance of the image plane to different distances does not fix the problem; it's still a planar image with a planar wavefront, which causes eyestrain, fatigue and nausea.

Stereoscopy

Most Near-to-Eye (NTE) optical systems create 3D images by using two slightly off-set planar images to create a stereoscopic effect. They use the camera frustum to try and set a perceived distance, but a planar wavefront does not contain enough mono and stereo cues to allow the visual cortex to properly perceive and determine depth. This forced 3D vision effect is what causes so many people to be unable to watch 3D content for any length of time without eyestrain or nausea. It is unnecessary and undesirable to try and force vergence, that is <u>not</u> how the human visual system works. The actual perceived volume of vision comes as a result of each piece of light reaching the eye at different times, coming from many different angles. It is the multi-angular freeform wavefronts and their time differential that creates the volume we perceive. This rich data provides the necessary mono and stereo cues to determine depth properly.

Time differential is one of the major contributing factors used by the brain's visual cortex to determine depth. Stereoscopy or parallax is one component of depth perception. If stereoscopy parallax were the main factors resulting in our volumetric perception when we look at the world around us, everything would collapse into a flat plane if we covered one eye. Our brain uses multiple factors to create a 3D view, but the primary component to generate a volume is time.

Mirror-Based Optics

The only device known today that relays Volumetric Imagery is a mirror. Since we can only "see" something if light is reflecting off of it, you could say that the whole world is a mirror, it reflects light into our eyes, and the brain's visual cortex makes a Volumetric Image out of the data. The other amazing attribute of mirrors is that everything in a mirror is always in focus by simply choosing what to look at, they are what is called accommodation invariant. There are no "image planes" in a mirror, mirrors relay a volume, they produce Volumetric Imagery at every distance.

As an example: when you look in the bathroom mirror to shave or put on makeup, you are in focus even if you are only a few inches away. Or if you look in the rearview mirror of your car at the kids in the backseat, they are in focus. If you decide to look at something 300 feet behind you, that is also in focus, simply because you decided to focus your attention on something else. This happens because freeform wavefronts are being received by the eyes from all depths and multiple directions simultaneously.

To eliminate the Vergence Accommodation Conflict, a head-mounted display must follow the rules of how humans see the real world; it must create a freeform wavefront Volumetric Image. This can be accomplished by using multiple freeform, off-axis compound curved, first surface mirrors.

The IMMY Solution

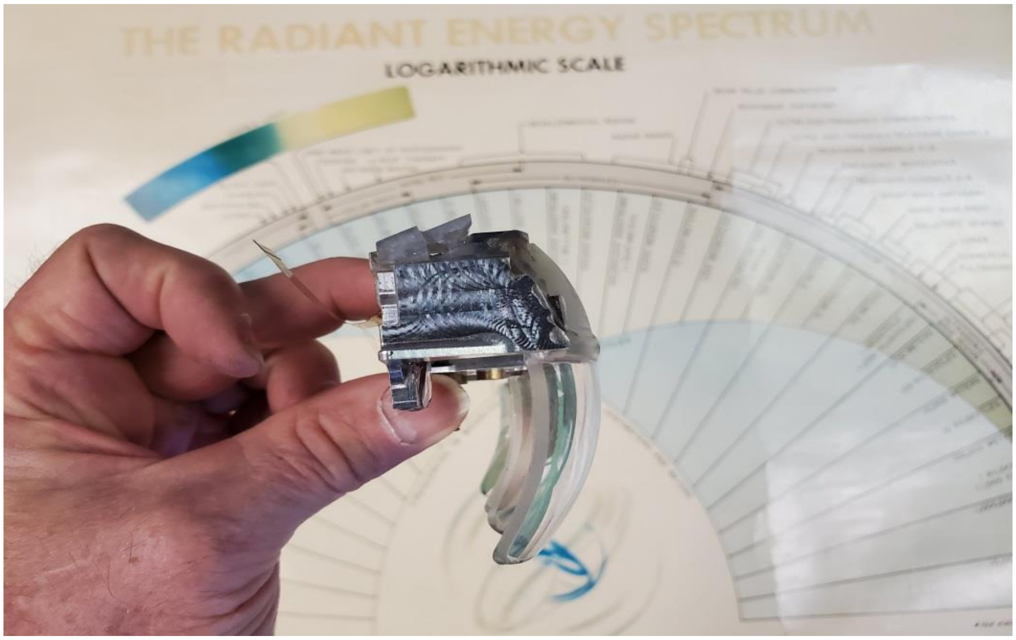
This is how the IMMY 3 mirror, freeform compound curve, off-axis system works:

First: The M1 bi-concave mirror starts the conversion of the original 2D OLED display light rays into a freeform wavefront. The original Lambertian (hemispherical radiation) distribution of light energy is converted into a volumetric display using a bi-concave freeform mirror [see M1 below). The hemispherical wavefront enters the bi-concave M1 mirror with a time differential, hitting different locations on the curved surface at different times.

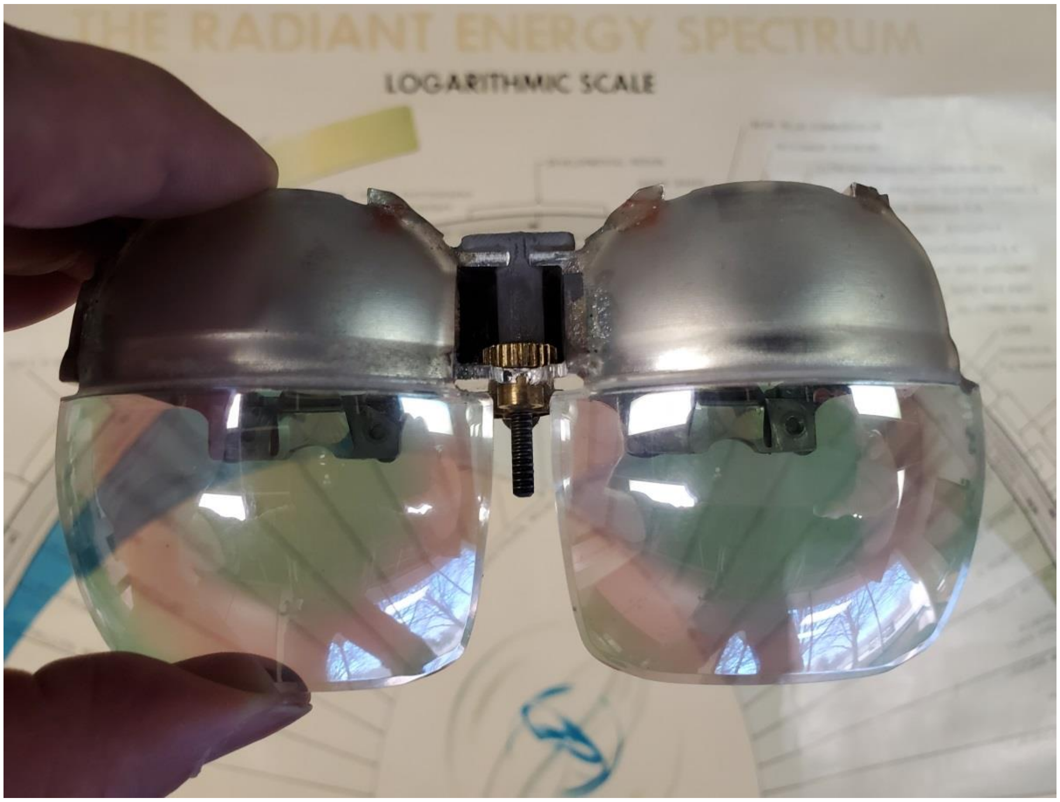
Second: This compound curve freeform first surface mirror causes a super-sampling (upscaling) of the original 2D flat display to be "seen" as a volume by the M2 mirror. This provides a true volumetric freeform wavefront being relayed into the magnifying mirror, M2 [see M2 below]. Every point of every pixel from the display is visible at every point on the curved M1 mirror, enabling the entire image volume to be relayed to the M2 with a complex time signature. This occurs as an off-axis inversion, where the rays from the M1 converge on top of one another on the M2, at approximately a 30:1 reduction in area.

Third: This incredibly complex freeform wavefront is relayed to the M3 (combiner) mirror via the M2 compound convex freeform [see M3 below]. The M3 is where the ray bundle is unbundled and collimated, relayed directly through the pupil and onto the retina, creating a true lightfield Volumetric Image.

CROSS-SECTIONAL VIEW OF A FULLY REFLECTIVE NEAR-TO-EYE, MIRROR OPTIC SYSTEM



Side View of the IMMY Optic Engine

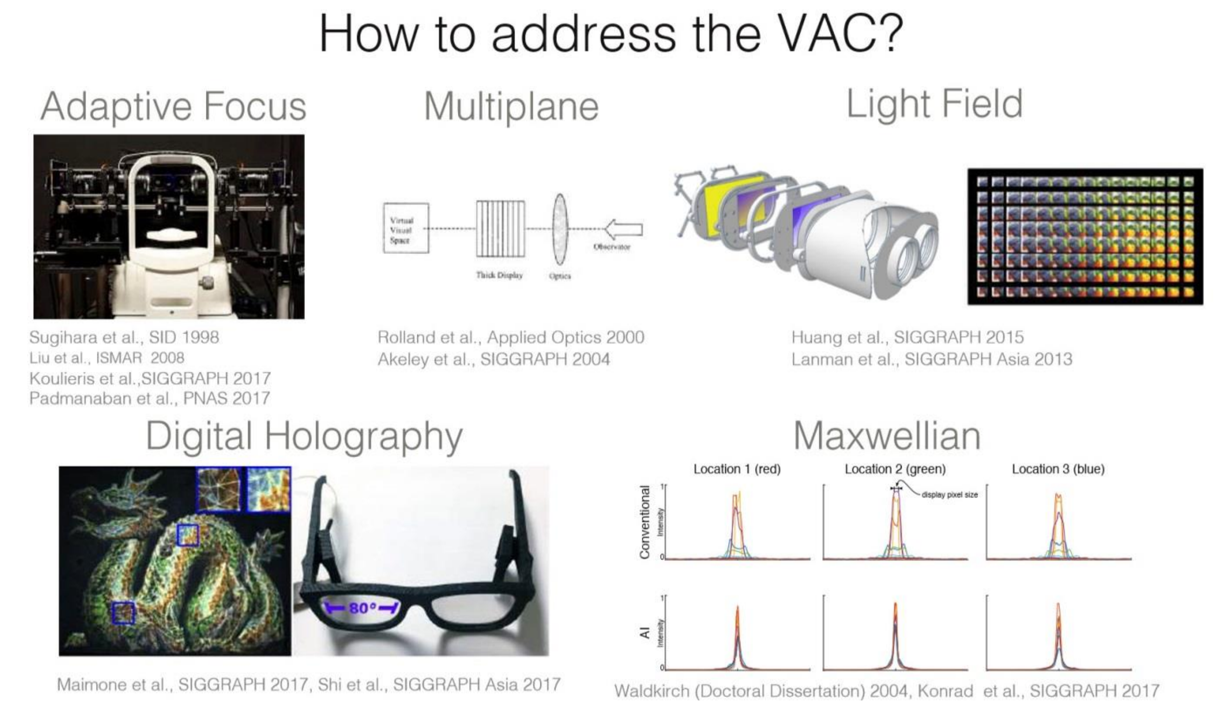


Front View of the IMMY Optic Engine

The curved mirrors create multiple viewing angles of the source imagery, allowing the eye to move around freely, absorbing freeform wavefront light energy from many different angles. This natural process of absorbing and processing both mono and stereo cues produces an in-focus image at the proper depth by providing sufficient data to the visual cortex. This addresses the basic needs of Human comfort, Human safety, Eye comfort, and Eye safety and generates an extremely large Depth of Field, with a very large eyebox.

Current efforts to solve the VAC

There have been many attempts to correct the lens-induced VAC problem. Below are several examples of attempts to solve the VAC published from a SIGGRAPH presentation [3]. Any headset that uses lenses will thus suffer from VAC and will require the implementation of some form of correction. These correction methods are computationally intensive, expensive, and in most cases induce additional eyestrain, human factor issues, weight, and cost. A lot of work has been conducted with deliberately blurring portions of the image, to try and trick the brain into understanding the depth of an image. Forcing the eye to accommodate with blurring and PSF (point spread function) contrast causes eye strain and does not resolve the real-world disparity issue. In other words, it doesn't really work. The human vision system is far too complex for this issue to be solved artificially. Perhaps even more importantly, most of these attempted solutions are simply changing the focal distance of the generated planar wavefront, which is not a solution to the actual problem. The real problem is how to get freeform light into the eye, not a planar wavefront.



How to address the VAC?

Adaptive Focus

Sugihara et al., SID 1998
Liu et al., ISMAR 2008
Koulieris et al.,SIGGRAPH 2017
Padmanaban et al., PNAS 2017

Multiplane

Rolland et al., Applied Optics 2000
Akeley et al., SIGGRAPH 2004

Light Field

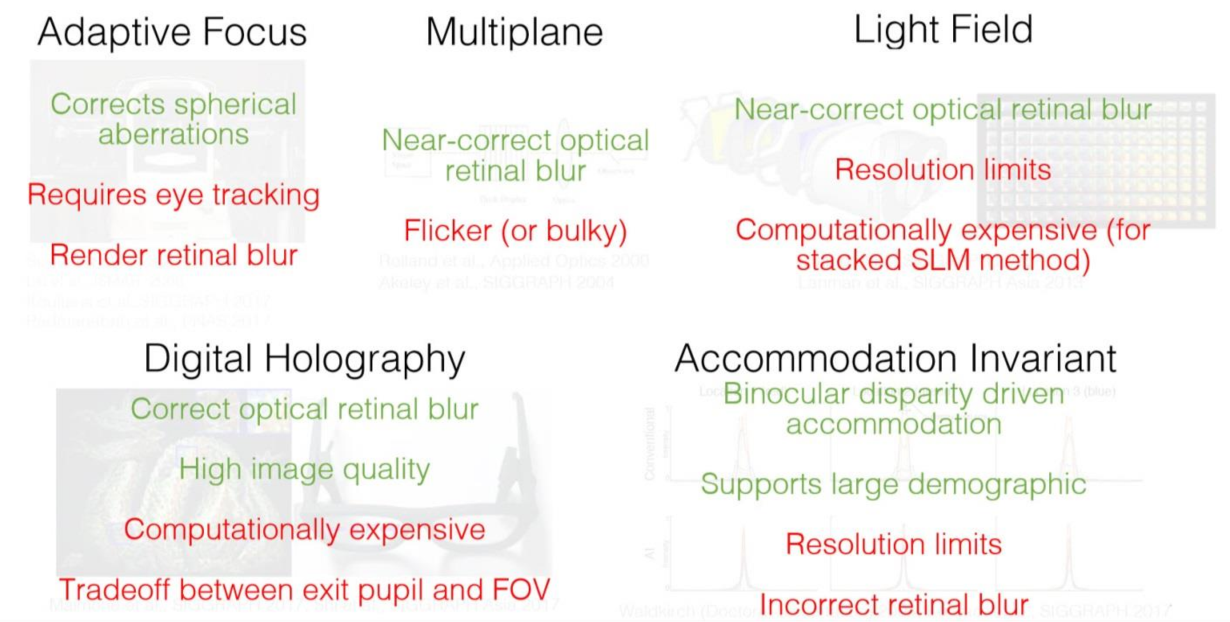
Huang et al., SIGGRAPH 2015
Lanman et al., SIGGRAPH Asia 2013

Digital Holography

Maimone et al., SIGGRAPH 2017, Shi et al., SIGGRAPH Asia 2017

Maxwellian

Waldkirch (Doctoral Dissertation) 2004, Konrad et al., SIGGRAPH 2017



Adaptive Focus

Corrects spherical aberrations

Requires eye tracking

Render retinal blur

Multiplane

Near-correct optical retinal blur

Flicker (or bulky)

Light Field

Near-correct optical retinal blur

Resolution limits

Computationally expensive (for stacked SLM method)

Digital Holography

Correct optical retinal blur

High image quality

Computationally expensive

Tradeoff between exit pupil and FOV

Accommodation Invariant

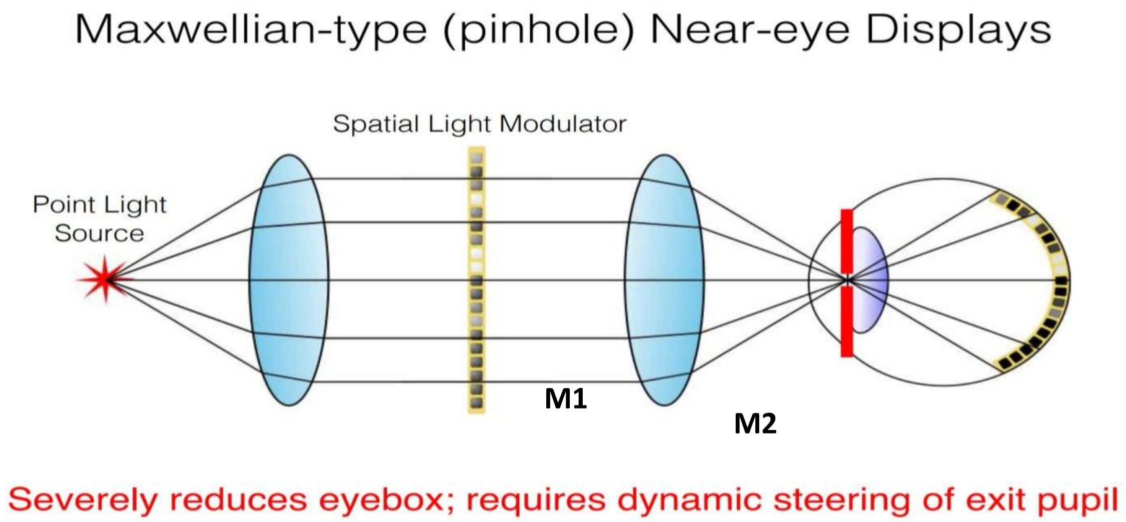
Binocular disparity driven accommodation

Supports large demographic

Resolution limits

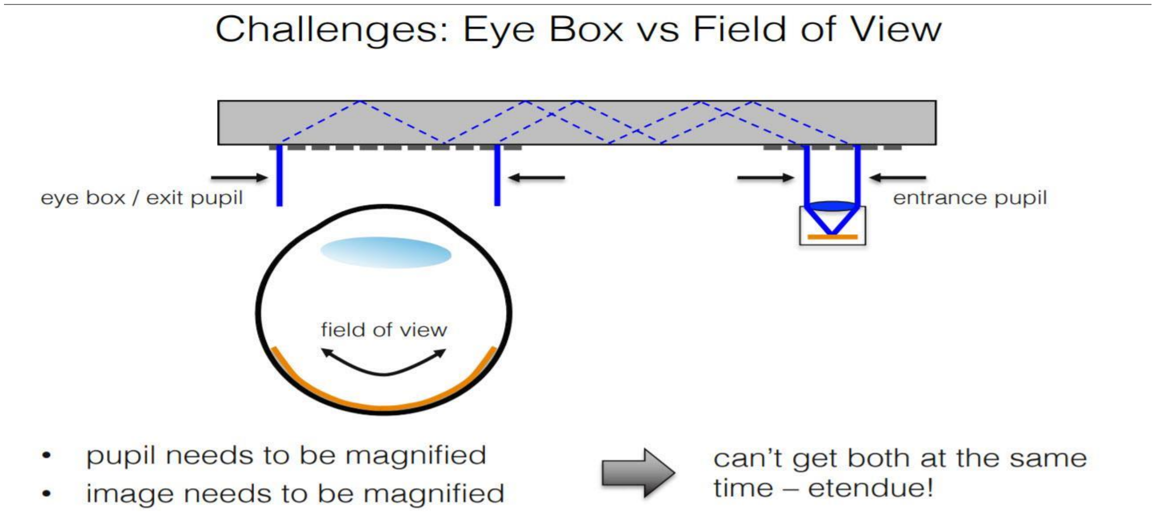
Incorrect retinal blur

Below are additional slides from the same SIGGRAPH presentation [3] showing the Maxwellian problem and the waveguide problem of a small eyebox.



Maxwellian-type (pinhole) Near-eye Displays

Severely reduces eyebox; requires dynamic steering of exit pupil



Challenges: Eye Box vs Field of View

- pupil needs to be magnified
- image needs to be magnified

can't get both at the same time – etendue!

Conclusion:

After decades of attempts and billions of dollars to produce an economically practical, eye-safe and comfortable AR/VR/MR/XR headset, without satisfactory results, it seems obvious that something is wrong with the lens-based waveguide optical approach. Curved mirrors, which naturally generate Volumetric Imagery, provide a practical solution and are a material paradigm shift in how HMD's should be built. Working in harmony with how the Human vision system operates should be the central theme of HMD design. AR and VR headsets must present as natural and unadulterated freeform wavefront imagery as possible into the eye; the visual cortex does the rest.

If the desired application for the "glasses" is more than simple data, then planar wavefronts are problematic. True immersion and volumetric imaging require freeform wavefronts. This means that the "combiner" lens must be curved to be able to deliver multi-angular light rays, (with the correct time signature), into the eye and visual cortex, and therefore will not look like ordinary glasses. Attempts will continue to be made to synthesize the needed freeform wavefronts to try and make these glasses look like regular glasses and not cause the VAC, maybe someday that will be possible, ut a practical solution seems unlikely. We believe a great user experience is the foremost consideration when using these "glasses" and that a natural, eye safe organic solution is best – it's as simple as looking in a mirror.

Bio:

Doug Magyari CEO/CTO IMMY Inc.: Inventor, scientist, entrepreneur, and visionary, Doug has spent more than 20 years working with immersive technologies and developing augmented reality (AR) headsets. He has 15 patents in chemistry, optics, acoustics, mechanics, and electronics with additional patents pending. He has started, operated, and sold six different companies.

For more information on Volume Imaging, the IMMY Mirror Optic System, and the IMMY Immersive Imaging Glasses visit IMMYinc.com or contact us at: info@immyinc.com

References:
1. David M Hoffman, Ahna R. Girshick, Kurt Akeley, and Martin S. Banks (2008) "Vergence-accommodation conflicts hinder visual performance and cause visual fatigue" J Vis.; 8(3) 33.1-3330 https://www.ncbi.nlm.nih.gov/pubmed/18484839

2. Gregory Kramida and Amitabh Varshney (2015) *IEEE Explore,* IEEE.org "Resolving the Vergence_Accommodation Conflict in Head Mounted Displays". https://ieeexplore.ieee.org/abstract/document/7226865/authors#authors

3. R. Konrad, N. Padmanaban, K. Molner, E.A. Cooper, G. Wetzstein (2017) "Accommodation-invariant Computational Near-Eye Displays", ACM SIGGRAPH (Transactions in Graphics 36,4). http://www.computationalimaging.org/publications/accommodation-invariant-near-eye-displays-siggraph-2017/

Author Keywords

Augmented Reality; Virtual Reality; Mixed Reality; Vergence Accommodation Conflict; Volumetric Imagery; Lightfield.