Paper Title: Novel 360-Degree Camera

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***Abstract* — Circle Optics is developing novel technology for low-parallax, real time, panoramic image capture using an integrated array of multiple adjacent polygonal-edged cameras. This technology can be optimized and deployed for a variety of markets, including cinematic VR. Circle Optics' existing prototype, *Hydra Alpha*, will be demonstrated.**

***Keywords* — Parallax, Optics, Panoramic, 360° Camera, AR/VR, Defense, Aerospace, UAVs**

Pre-existing multi-camera panoramic devices, such as the Insta360, capture content with overlapping fields of view to compensate for, or limit, blind regions between spatially offset, round aperture, cameras. These devices are then burdened by parallax and time-consuming image stitching, which together can impart significant image artifacts in the resulting composite panoramic image. To address this, Circle Optics is developing a novel multi-camera technology, in which the individual camera channels are tapered inwards from outer polygonal cut lens elements, such that the channels can be assembled into a geometrical shape (e.g., a dodecahedron) with minimal gaps or seams between the channels. Additionally, the lenses are optically designed to limit parallax or perspective errors. In combination, these features provide real-time panoramic imaging from the plurality of camera channels with easy image tiling and minimal parallax-based image artifacts.

Fig. 1. Image of the Hydra Alpha camera system.

Circle Optics has a demonstratable prototype system, *Hydra Alpha*, and a second-generation system, *Hydra Beta*, under development. In addition to these cinematic VR targeted systems, Circle Optics is also developing specialized systems for NASA, the US Air Force, and for use on UAVs, where real-time wide field situational awareness is highly valued.

Circle Optics will demonstrate the *Hydra Alpha* system and discuss the evolution of the technology and its potential for application for a variety of markets.

I. The Parallax Paradigm

Although most people are unfamiliar with parallax or its properties, we rely on it every day to help enable our stereo image depth perception. Visual parallax is essentially enabled by the interocular distance, or gap between human eyes, which averages ~63.5 mm for adults, and our eye rotation. Parallax means the ability to see an object in two different ways. It is a displacement or difference in the apparent position of an object viewed along two different lines of sight and is measured by the angle or semi-angle of inclination between those two lines. Along with lighting and shading, overlap or occlusion, linear perspective, and motion, parallax is a depth cue that helps enable human stereo depth perception. Human ocular parallax, which includes the change in perspective as the eye rotates, varies with object distance, as a person fixates on different parts of a scene. The brain then fuses the two instantaneous images to provide stereopsis, or the perception of depth produced by the reception in the brain of visual stimuli from both eyes in combination.

As another example, motion parallax is a monocular depth cue that arises from the relative velocities of objects moving across the retinae of a moving person, such that people see objects nearest to us moving faster than far away objects. This phenomenon is true whether the object itself that is moving or the observer/camera that is moving relative to the object. Stellar parallax is a special case of motion parallax, applied in astronomy, in which the relative motion between the Earth and near and distant starts can be used to estimate astronomical distances in light-years or parsecs.

In cinema, stereo parallax, which is similar to visual parallax, relates to how two cameras are positioned relative to separation distance and tilt or skew, when shooting movies. The same visual cues, such as lighting, motion, parallax, and perspective differences, are present in the two images. However, when the images are subsequently displayed or projected on a flat screen the sense of depth is generally lost, and the parallax differences in the images can be seen by the audience as displacements or offsets between the two superimposed images. This is then overcome by encoding the left and right images by control over the polarization or color of the display light, and having the audience members wear the appropriate decoding glasses.

However, parallax is rarely considered as an optical property relative to how an individual camera lens system is designed, or how adjacent camera systems are mounted relative to each other. Even in photogrammetry, which is the field of obtaining reliable measurements or 3D information about physical objects and the environment through the process of recording, measuring and interpreting photographic images, a simple pin-hole camera model is typically assumed, while the details of the camera performance or design are overlooked. As one counter example, companies that develop riflescopes are concerned with a version of motion parallax, where a change in the alignment of the user's eye, relative to the riflescope and the reticle thereof, can cause a misaiming to occur. Riflescopes are specifically designed to reduce or eliminate this issue.

II. The Circle Optics Camera Systems

Circle Optics is developing optical and opto-mechanical designs for the individual camera channels, and for the devices or systems. In overall architecture, these systems can be spherical, like *Hydra Alpha*, hemispherical, conical, or annular, with pentagonal or hexagonal camera channels arrayed in the patterns of specific Goldberg polyhedra. Although the cameras characteristically use polygonal lenses to capture polygonal images with polygonal fields of view, for the more complex polyhedral shapes, the individual camera channels can have different maximum imaged fields of view. To enable more sensor options and dual simultaneous sensing modalities, the systems can also include relay lenses and secondary sensors.

The camera channels in the original *Hydra Alpha* prototype system were developed using a novel lens design approach in which the projection of the chief rays is optimized to help control parallax.[1] The camera channels were then mounted in lens housings, and the housings were mounted together using a piecewise internal framework. As of this writing, one of the *Hydra Alpha* camera channels is inoperable as the outer lens element came out. This loss is attributed to an inadequate kinematic design which allowed internal mechanical stresses to be applied against the camera channel housings. Circle Optics has developed subsequent optical and mechanical[2] designs which have improved the potential system performance in myriad ways. For example, large high-resolution systems can be developed for military applications that can be deployed on aircraft or satellites. As another example, light weight systems with plastic optics can be developed for potential use on commercial or military drones. Circle Optics is presently working on a variety of device architectures, including ones whose shape and size is on the order of 10mm radius or approaching the size of a golf ball.

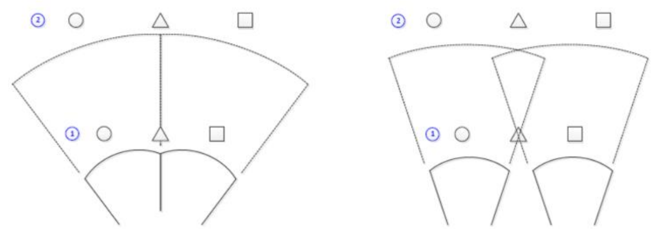

Fig. 2. The image on the left shows how Circle Optics' fields of view align while the image on the right represents how comptetitors' fields of view overlap producing parallax.

Of course, images captured by adjacent cameras can have color and intensity differences, due to differences in spectral transmission, lens assembly, maximum fields of view, and sensor responsivity. Image appearance between adjacent cameras can also occur from abrupt variations in scene brightness between cameras. Circle Optics is developing image calibration software and tools, including for both intrinsic and extrinsic calibration, so as to address such issues.

In comparison to the prior *Hydra Alpha* system, the *Hydra Beta* system, which will be operational in Q1 2022, not only will have improved optics and opto-mechanics, but it will support higher resolutions and frame rates, which can make it a viable demonstration system for the high-end cinematic VR markets. In combination across a plurality of cameras, this system will image 8000 equatorial pixels. While this system is best suited for wide field of view image capture at short distances, other design optimizations that provide much higher resolutions, could be used effectively for cinematic VR to capture scene content at much greater distances. Circle Optics has over 20 letters of intent from participants in the cinematic / VR market who have an interest in at least testing the *Hydra Beta* system.

III. Conclusion

Circle Optics technology can provide a unique combination of wide field or panoramic imaging, in real-time with low distortion, by cropping and tiling adjacent images together, while having minimal residual image artifacts. Thus, this technological advancement can provide benefits in many fields or applications, including Cinematic VR, photogrammetry or mapping, navigation, and security or surveillance, with resolutions ranging from 20-400+ pixels/degree, depending on the lens design and the polyhedral geometry.

Fig. 3. *Example of real-time output from the Hydra Alpha camera system captured in Times Square.*

IV. REFERENCES

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VII. MEDIA

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