AIAA 92-2805

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AIAA SDIO Annual Interceptor Technology Conference
May 19-21, 1992 / Huntsville, AL

A HEMISPHERICAL IMAGING AND TRACKING (HIT) SYSTEM

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Abstract

This paper describes a hemispherical imaging and tracking (HIT) system for an interceptor designed to acquire, select, home, and hit-to-kill reentry vehicle targets from intercontinental ballistic missiles.

Description of the HIT System

HIT is a lightweight system with no moving parts that relies on a panoramic annular lens (PAL) and a reflector to capture and track images in real time within a hemisphere.

The panoramic annular lens (PAL) which consists of a single optical substrate with spherical surfaces has been used in a number of different prototype systems designed for panoramic inspection and measurement.[1-4] It relies on a revolutionary new design based on reflection and refraction of light to produce a flat annular image of the entire 360 degrees surrounding the optical axis of the lens. A virtual annular-shaped image of its surroundings is formed inside the lens. This virtual image can be imaged onto a sensor by the use of a transfer lens. Figure 1 shows the geometric structure of the PAL. The thick lines indicate reflecting surfaces.

The cylindrical region surrounding the PAL is optically transformed, using stretching methods, onto a flat surface by a phenomenon called Flat Cylinder Perspective (FCP). In FCP mapping, all parallel rays are focused to a single point, unlike the traditional perspective technique in which parallel lines with different directions are focused to different points on a line (the horizon). Figure 2 illustrates flat cylindrical perspective and shows the limiting angles involved in determining the field of view. In the design of the lens it is desirable to make α large and β small so as to maximize the viewing area. The value of these parameters are constrained, however, by the limited range in the index of refraction that can be obtained in commercially available materials. The lens produces an annular image with a width corresponding to

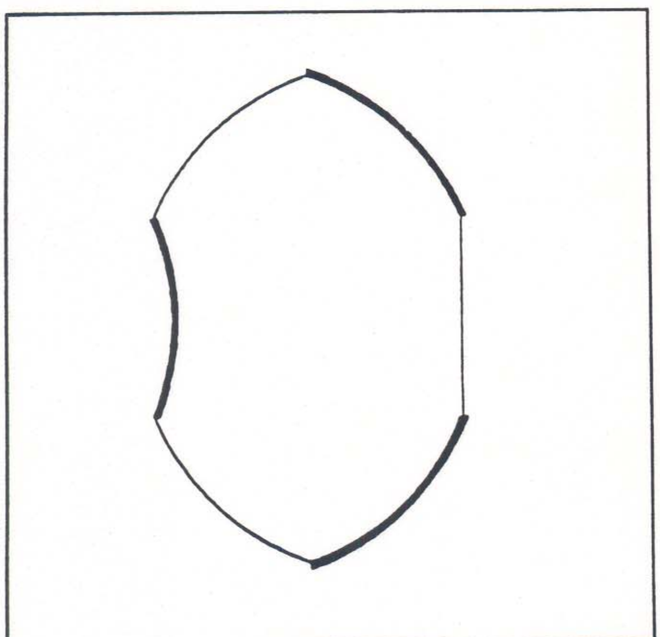

Figure 1. Physical shape of a panoramic annular lens (PAL).

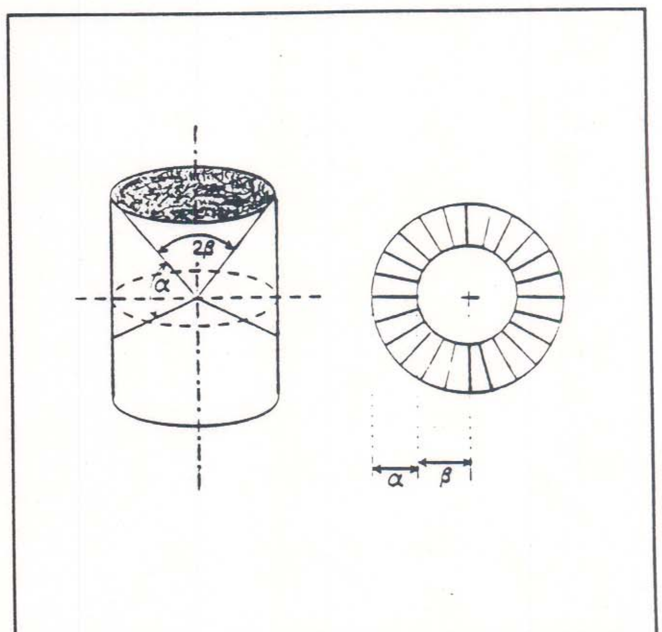

Figure 2. The PAL forms an image using flat cylindrical perspective.

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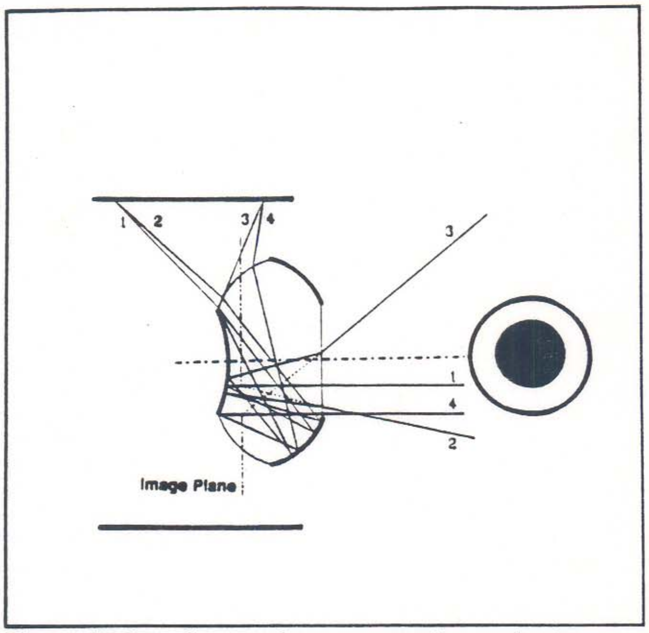

Figure 3. Ray diagram for a panoramic annular lens.

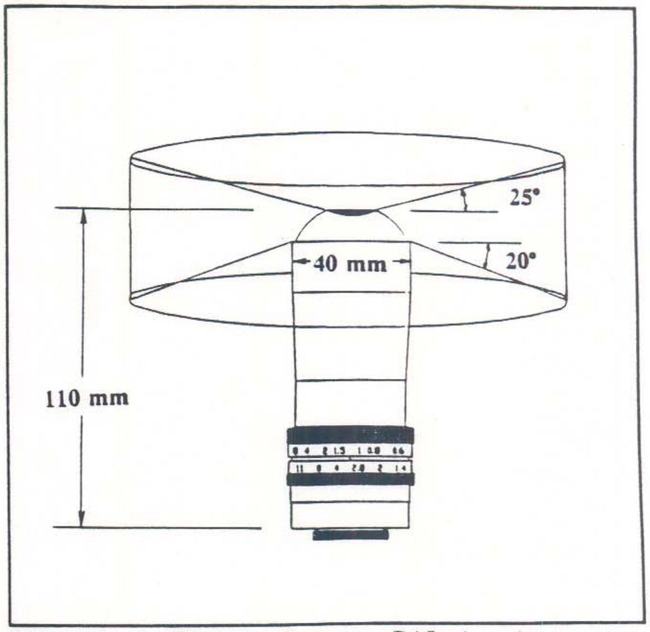

Figure 4. A 38 mm diameter PAL imaging system manufactured by Optechnology, Inc.

the size of the acceptance angle α and each concentric ring in the image plane representing the locus of points recorded at a fixed angle to the optical axis. A ray diagram illustrating how light rays traverse the lens and form a virtual image inside the PAL is depicted in Figure 3.

Figure 4 shows the PAL system used for HIT and illustrates that a transfer lens can be used to image the internal virtual annular-shaped image onto a focal plane array. The system includes a 38 mm-diameter PAL and an f/1.4, 25 mm focal length transfer lens. The field of view extends from approximately -20 degrees below the lens to approximately 25 degrees above the lens ($\alpha = 45°$; $\beta = 65°$). Optics are packaged with a "C" mount so that the system can be attached to a standard video camera.

In order to achieve true hemispherical viewing, HIT relies on a reflector placed behind the PAL to create an image of the region forward of the lens. The system is constructed so that the image obtained by the mirror may be captured directly through the PAL. Consequently, a target slightly above the horizon is captured by the PAL and observed approximately midway between the inner and outer boundaries of the annular image. As the system is progressively aligned with the target, the object continues to be captured directly through the PAL and moves toward the inner radius on the image plane. When the target is 65° off axis, measured from the optical axis, light from the target now reflects off the mirror and is subsequently captured by the PAL. The result appears in the annular image slightly offset from its initial position in the radial direction. As the target progressively comes into alignment with the optical axis of the system, its image moves toward the outer radius in the annular image plane. When the optical axis and the target are directly aligned, the target is observed by all points on the circumference of the mirror and a distinct circular ring is observed in the image plane.

The HIT system is schematically illustrated in Figure 5. Signals scattered from a target contained in the hemisphere forward of the interceptor pass through the viewing window {1}. Rays contained within the angle α are collected directly by the panoramic annular lens {2}, while the rays contained within the angle β initially reflect off an annular mirror {3} and are subsequently captured by the PAL {2}. The virtual image formed within the PAL is transferred by the transfer lens {4} to a focal plane array {5}.

Prototype Development

A prototype for HIT was fabricated and tested by placing it on a kinematic stage having one degree of freedom. A small diffuse light source was used to simulate the target at a fixed distance. Figure 6(a) shows the image of the source observed when the target is more than two degrees off-axis. As the system is driven 'on target', diametrical signatures are observed. This is evident in Figure 6(b) which shows the image captured when the target is at two degrees off-axis. Figure 6(c) shows the characteristic circular ring which appears when HIT finds its mark and is directly 'on target'.

The 'on target' signal is generated when rays imaged toward the outside of the annular image are reflected from points located on the circumference of the rear reflector.

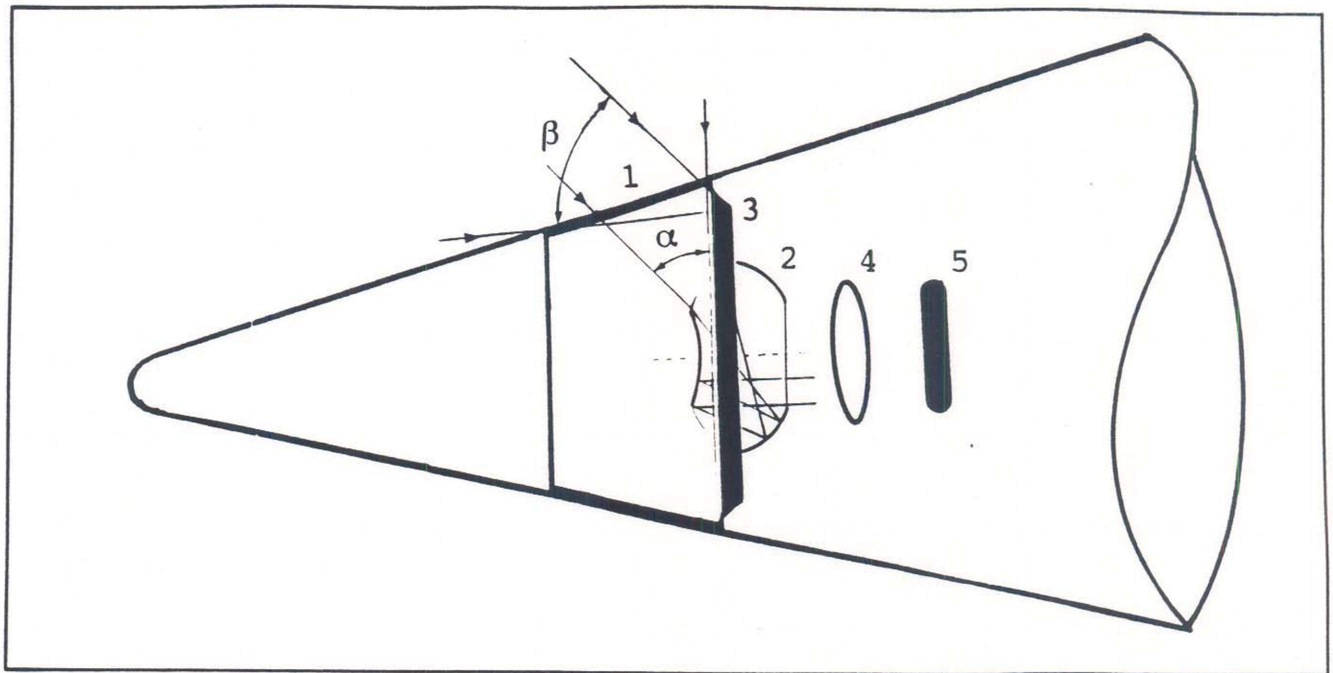

Figure 5. Optechnology's hemispherical imaging and tracking (HIT) system placed inside an interceptor.

These rays emanate from a focal point on the optical axis forward of the lens system. A target contained in the conical region forward of the focal point forms a distinct ring in the image plane. The uniformity of the ring depends on the location of the target in the region. When the optical axis is directly aligned with the target a uniform circular ring is produced in the image plane. Assuming that the target is on axis, the overall intensity of the ring increases as the distance between the lens and the target decreases. The intensity becomes maximum when the target reaches the focal point; the ring disappears as the target enters the occluded region immediately forward of the targeting system.

The proposed system can be incorporated with an electro-optic and control package to drive the system on target with potentially minimal calculations. One scenario would be to locate the centroid of the target in the annular image. The position of the optics would be computationally adjusted to drive the image toward the outer radius in the annular image plane until a circular ring is formed; that is, the system is 'on target'. The uniformity of the ring would be established by comparing the intensity of three or four pixels equi-spaced around the circumference of the ring. Through the control loop, the system would be maintained 'on target' by equalizing the intensities of the pixels. Once aligned, the computer

Figure 6. The image obtained from the HIT system with the target (a) at more than two degrees off-axis, (b) at two degrees off-axis, and (c) directly on-axis.

would continue to monitor the intensity until the target is at a predetermined critical distance from the system.

One advantage of this approach is that the computationally intensive calculations for determining the centroid of the target and for tracking may be performed early in the targeting cycle. Since the comparison of intensities at a discrete number of fixed points is relatively simple, more calculations and associated corrections can be made during the critical alignment stage.

System Refinement

Progress has been made to study the speed of the PAL, its imaging characteristics (aberrations), and the modulation transfer function. Parameters which can be adjusted to improve image quality have been determined. Tests performed to evaluate the spectral bandpass of the PAL illustrate that it performs best in the visible and near infrared. Future plans for advanced optical design and fabrication will move most of this work into the 3-5 micron infrared regime.

The current HIT system utilizes a PAL and an auxiliary optical mirror to allow imaging within a hemisphere using no moving parts. As the target moves in an angular direction off the horizon, it is imaged directly by the PAL. In the image plane, the image of the source moves across the annulus from the outer radius to the inner radius. When the target is 65° off axis, measured from the optical axis with respect to the outward normal of the target, light from the target reflects off the mirror and is subsequently imaged by the PAL. A path reversal of the image is noted at this point and is characterized by the image shifting tracking directions; the image of the source now tracks from the inner radius to the outer radius in the annular image plane as the target and optical axis move toward alignment. This path reversal is undesirable and will be eliminated by redesigning and repositioning the rear reflector with respect to the PAL. With the existing PAL design, the circularly symmetric region over which the target can be tracked is limited to approximately 160°. However, with proper redesign of the lens, it may be possible to restore hemispherical viewing.

Conclusion

A Hemispherical Imaging and Tracking (HIT) system has been described which not only provides a sizable field of view over which a target may be tracked, but also yields a unique and distinctive optical signal when the system is 'on target'. The depth of focus of the system is infinite and there are no moving parts required to image within a hemisphere.

Overall, the system may have a significant advantage over other systems designed which look forward through a window in a single direction. In this case, signals may become distorted due to blur and jitter. Critical alignment of the HIT system relies on the comparison of signals captured through different points on an annular window. Assuming that the perturbations are radially symmetric, errors may be eliminated during the subtraction.

The HIT system may also be utilized in unconventional viewing locations. Problems with aerodynamics and thermal heating occur when a window is required to be placed in the vehicle. Severe restraints on the angle of the window result. For applications that do not require hemispherical viewing, the HIT system offers potential advantages to overcome the aforementioned problems; the optics associated with HIT may be placed at any angle on an unconventional site on the vehicle. This alternative could possibly allow the window to be placed at a shallow angle in a region not as severely affected by thermal gradients. The optical signal characteristic of the system positioned 'on target' would not be produced, however, and this would require the development of more intensive computational schemes to drive the system to the required position.

Acknowledgements

Portions of the work described were supported by Optechnology, Inc., and by the U.S. Army Strategic Defense Command under Contract No. DASG 60-89-C-0145.

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