Range Finding using a Masked Annular Folded Optic Imager

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Abstract: High-resolution images of an unfocused laser beam were obtained by masking the aperture of an annular folded optic imager. Image processing yielded calibrated distance measurements correlated to the separation of the beam spots.

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Numerous mobile applications benefit from range finding technologies, including but not limited to conventional surveying, robotic navigation, and hand-held imagers. Recent surveys in optically based measurement devices detail numerous different techniques [1,2]. The predominant method used commercially is time of flight (TOF) that uses the amount of time required for a light pulse to reflect back to a high-speed receiving detector. Other techniques use multiple frequency phase-shift or a CCD or CMOS imager to interpret laser projections and effects such as speckle sectioning, moiré patterns, and structured lighting. The imaging disadvantage of higher processing requirements comes with the added benefit that these methods can provide direct correlation between pictures and distances as well as measure short ranges, often less than 1m that TOF cannot accomplish inexpensively. This paper leverages recent developments in folded optic imagers to create a CMOS-based range finder that accurately resolves distances while using minimal computational processes. The enabling technology is the application of a pupil mask to a folded optic imager that has an inherently narrow depth of field.

The folded optic imager is a reflective multiple-fold approach to imaging that provides high resolutions and a large aperture with reduced thickness [3]. The loss of bulk and weight makes this system an ideal candidate system for mobile platforms such as search and rescue robotics and infrared cameras.

The optical path is folded in Figure 1, which constrains the thickness while increasing the diameter similar to the Schmidt-Cassegrain telescope with additional folding to improve the field-of-view (FOV). The result is a telephoto lens design with a 6.7 degree FOV and a numerical aperture of 0.71. Coupled to the lens is an Omnivision 3610 CMOS sensor. The design could be optimized for conjugates from 2m out to infinity but a fixed focus object distance of 2.7m was chosen based on the availability of a prototype.

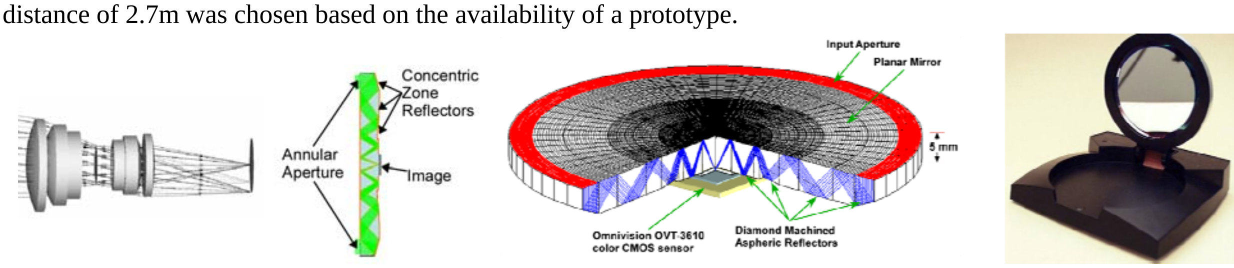

Figure 1. Conventional ray path and a folded ray path (left), diagram of folded optic lens and sensor (center), and imager in packaging (right).

The high relative obscuration of the lens results in defocus patterns that are detected as rings by the sensor rather than blur. Combined with the numerical aperture of this specific design, the folded optic has a small depth of focus that corresponds to a higher resolution sensor image for range detection when coupled with a pupil mask. Apodized or shaped pupil lens systems are often used to tailor the point spread function (PSF) in astronomical research as a way to provide higher resolution for the star of interest [4]. Rather than working to improve the PSF, a pupil mask is applied to the folded optic imager to create multiple shaped apertures. The light rays associated with each aperture will have a concentric focal point however both converging and diverging rays will be separated as seen in Figure 2. For example, a mask that blocks all of the annular aperture except a point on the top and bottom of the lens could be visualized in geometric optics as permitting two rays to converge towards the same point. The inclusion of a laser source that projects a beam provides object illumination. If the beam were out of focus, then an imager would observe two points corresponding to the laser source. The distance between the points in the image is directly related to the distant the object is from the focal point. Non-symmetric masks provide an absolute measurement since the laser projection is inverted when the rays pass through the focal point. With knowledge of the focal length, the distance the object is from the focal point, and which side the object lies with respect to that point can be used to calculate the distance information of the object from the camera.

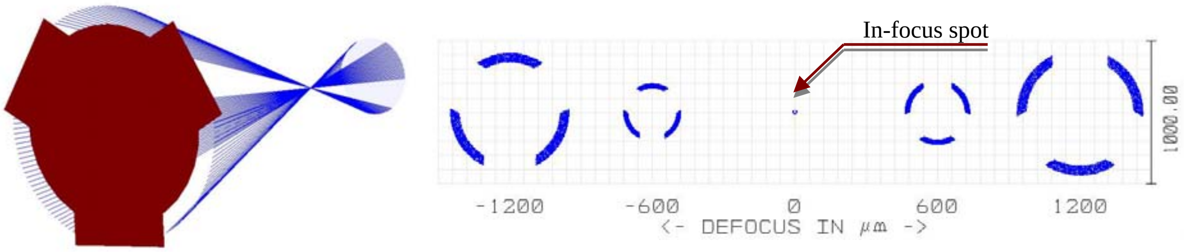

Figure 2. Computational ray tracing with paraxial lens with a 3 arc-segment pupil mask (left) and spot diagram (right).

The inclusion of a third, or odd-numbered aperture to the mask was included in the experiment to provide non-symmetry and redundancy for computer vision calibration. Once the laser source illuminates the desired target, the imager returns a picture similar to the theoretically derived spot diagram. Using an image processing tool such as Matlab or OpenCV, the centroid of each spot is calculated, one corresponding to each aperture segment. The distance between each centroid can be used to calculate the radius of a circle that would encompass all the spots. The radius is a figure of merit that can be directly correlated to the distance of the camera from the target.

In our experiment, a red laser diode was incident on a vertical reflective target that was moved with respect to a fixed camera. At numerous distances, images were saved and can be seen in Figure 3.

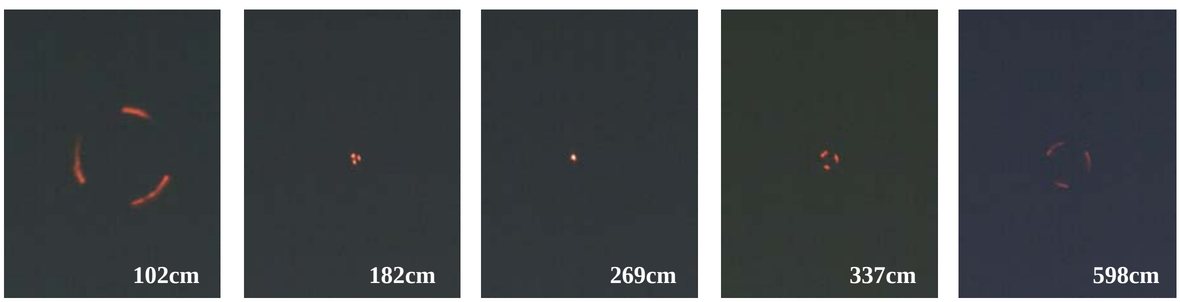

Figure 3. Five images demonstrate the changing radius of the aperture segments with distance. Note the observable vertical flip that occurs after the focal point (center image).

Image processing calculated the centroids of the red light segments in each image. The number of pixels between each segment provided three measurements of a radius that would encompass all spots. The average of those measurements was the figure of merit than provides the camera calibration for target distance seen in Figure 4.

Figure 4. Range of measured distances (50-600cm) vs. radial separation of beam points measured in pixels on the y-axis along with example photographs that combine imaging with range finding (beam spots circled).

The range finding system has both a minimum and maximum range due to the largest spot separation that can be resolved. However, the folded optic imager can be adapted to different focal lengths and FOV to accommodate other needs. Unlike the TOF systems, this method is best suited to short range environments. The author would like to thank Los Alamos National Laboratory for funding this research under a student fellowship.

[1] F. Chen, G. Brown and M. Song, “Overview of three-dimensional shape measurement using optical methods,” Opt. Eng. **39,** 10-22 (2000).
[2] F. Blais, “Review of 20 years of range sensor development” J. Electron. Imaging **13**, 231-240 (2004).
[3] E.J. Tremblay, R.A. Stack, R.L. Morrison, J.E. Ford, “Ultrathin cameras using annular folded optics,” Appl. Opt. **46**, 463-471 (2007).
[4] N.J. Kasdin, R.J. Vanderbei, D.N. Spergel and M.G. Littman, "Extrasolar planet finding via optimal apodized-pupil and shaped-pupil coronagraphs," The Astrophysical Journal **582**, 1147-1161 (2003).