

Multi-aperture Telecentric Lens for 3D Reconstruction

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We present a new telecentric lens which is able to gain 3D information. The proposed lens system has multiple aperture stops which enable to capture multi-directional parallel light rays, while a conventional telecentric lens has only one aperture stop, and can capture only light rays which are perpendicular to the lens. We explain the geometry of the multi-aperture telecentric system and show that correspondences fall on a line like those in a conventional stereo. As it is a single-lens sensor, we also introduce the principles of 3D reconstruction. Unlike a conventional stereo camera, the disparity of a scene point measured by the proposed lens system is linearly proportional to the depth of a scene point. © 2011 Optical Society of America

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Telecentric lenses have been widely used in many machine vision applications such as non-contact measurement and inspection systems [1, 2]. This is mainly because these lenses provide purely orthographic projections of scene points by locating an aperture stop at the focal point of a lens. This property makes it easier to measure or compare physical lengths of objects independently from the depths of the objects from the camera. However, this desirable property brings one drawback; it is not possible to obtain depth information from the image, as there is no foreshortening effect in telecentric images.

We present a new system for obtaining depth information while still preserving the advantages of a telecentric lens. The proposed system has multiple aperture stops rather than one, as in a conventional telecentric lens. A conventional telecentric lens selectively passes light rays which are *parallel to the optical axis*, because the aperture stop at the focal point of the object lens passes only the rays, as shown in Fig. 1(a). Light rays which are parallel to each other but not parallel to the optical axis converge at another point on the *focal plane*, which is perpendicular to the optical axis and passes through the focal point. Fig. 1(b) shows the ray diagram of a set of parallel light rays which are not parallel to the optical axis in a bi-telecentric lens. Assuming we have an infinitely small aperture stop, the light rays selected by the aperture stop are parallel to the vector from the lens center to the aperture stop.

Assume that there are two aperture stops on the focal plane, as in Fig. 2. One of the stops is located at the focal point of the lens, and the other is at a distance b from the focal point. For a scene point located at $(-z_1 - f, y_1)$, the light rays selected by the first and the second stops pass through the points $(f, -y_1)$ and $(f, -y_1 + (\frac{z_1}{f} - 2)b)$ at the image plane which is located at a distance f from the focal plane. The *disparity* d (displacement between two images) is

$$d = -(\frac{z_1}{f} - 2)b. \quad (1)$$

When $z_1 = 2f$, d becomes zero. Note that this disparity

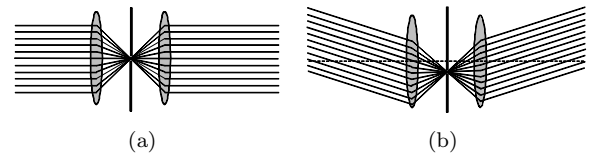


Fig. 1. Location of an aperture stop in a telecentric lens. (a) An aperture stop on the optical axis selects light rays parallel to the optical axis. (b) An aperture stop off of the optical axis selects different directional rays.

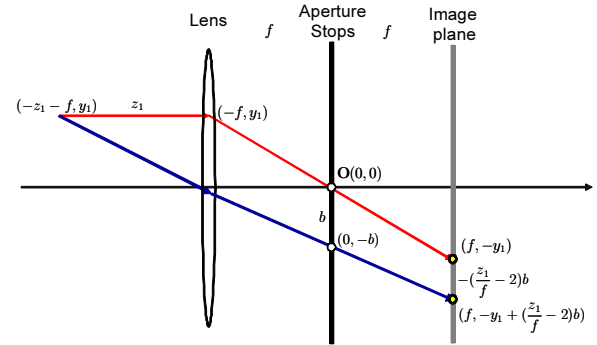


Fig. 2. Proposed telecentric imaging system with two aperture stops.

d can also be negative. In (1), both the baseline length b between two aperture stops and the focal length f of the lens are fixed. Thus, the disparity d is linearly proportional to the point depth z_1 from the lens. This is the critical difference from conventional stereo systems, in which the disparity is proportional to the *inverse depth* of a scene point. The *absolute* location of a point other than the depth can be easily obtained using the image which was captured by the aperture stop at focal point, just as in the conventional telecentric lens. Thus, the proposed lens will maintain the advantages provided by a conventional telecentric lens.

Though the idea to use multiple apertures is not new [3–7], to the best of our knowledge, it has not been

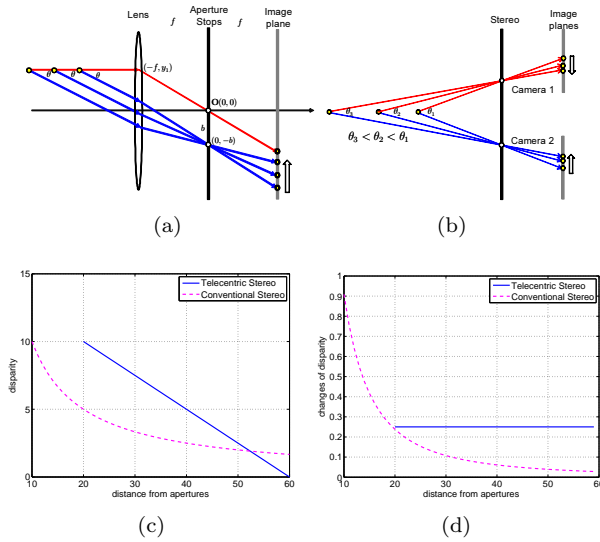


Fig. 3. Comparison between the proposed multi-aperture telecentric system (a) and the conventional stereo system (b) for objects in different depths from the sensor. Theoretical disparity and its first derivatives when $f = 20$ and $b = 5$ are presented in (c) and (d), respectively.

adopted in a telecentric lens. A telecentric lens with multiple aperture stops has a major advantage; the disparity given by the proposed *multi-aperture telecentric system* is linearly proportional to the depth, while that given by a conventional stereo system is proportional to the *inverse depth*, typically resulting in an unstable depth recovery [8]. Fig. 3 shows a comparison between the proposed system and a conventional stereo system. As the Fig. 3(b) shows, when a point goes farther, the angle between rays collected from the conventional stereo system becomes narrower, i.e., there is less disparity in the image space. The angle between the light rays collected by the proposed imaging system remains constant as shown in Fig. 3(a). As shown in Fig. 3(c) and 3(d), the disparity is linearly proportional to the scene depth, and thus, the sensitivity of depth estimation remains constant, an advantage of the proposed system. In addition, unlike the conventional stereo system, the proposed system does not require any photometric calibration or intensity adjustment between cameras because it is a single-lens imaging sensor. When the scene point is a Lambertian or a point light source, i.e. a source that emits the same amount of light in every direction, the brightness of the image captured by the proposed imaging system would remain constant.

The epipolar geometry in this multi-aperture telecentric imaging system is similar to a conventional stereo system. Fig. 4 shows the path of light rays traveling between the lens and the image plane for two scene points. The rays should pass through one of the two aperture stops, and build a pencil of planes containing the *baseline*. Because the image plane cuts the pencil of planes, all the correspondences should be on a line. For an im-

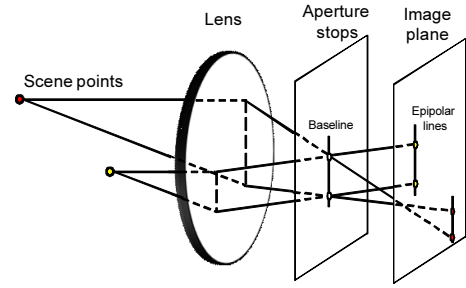


Fig. 4. Epipolar geometry on the image plane of the multi-aperture telecentric imaging system. A set of light rays building a pencil of planes.

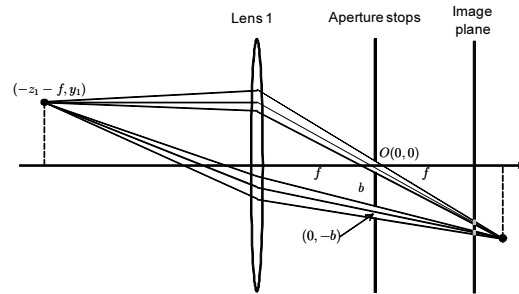


Fig. 5. Ray diagram of the multi-aperture telecentric imaging system. These stops are much larger than the actual size.

age plane parallel to the focal plane, all epipolar lines are parallel to the baseline and, of course, parallel to each other. Thus, the proposed telecentric lens which has multiple apertures generates a *rectified* image [8].

As a telecentric lens, each aperture stop selects light rays within a small range of angles, and also has small confusion circles. In addition, the confusion circle of each stop does not interfere with each other, thus the depth of field of the proposed system remains the same as that of the conventional telecentric lens. This is shown in Fig. 5, which gives a ray diagram of the telecentric imaging system with two apertures.

Fig. 6 shows our implementation of the proposed system using a Fresnel lens and an aperture stop plane. A lens, an aperture stop plane and an image plane lie on a linear rail guide. The focal length of the Fresnel lens measures 215 mm. It has three aperture stops with the baseline lengths of 30mm and 15mm. The diameter of each aperture stop is less than 1 mm. On the image plane, we placed a white square screen (190.5 mm × 190.5 mm).

Fig. 7 shows the images of a clear light bulb that appear on the screen when the distance of the light bulb becomes farther from the lens. The filament in the clear light bulb can be modeled as a set of point light sources. One can easily see that the disparity of a closer object is larger than that of a farther one. The input images in Fig. 7 were rectified using the four corners of the white screen. Once the rectified image was obtained, we

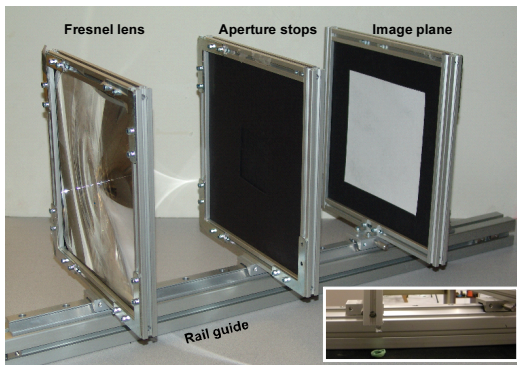


Fig. 6. Multi-aperture telecentric imaging system using a Fresnel lens with a focal length of 215 mm.

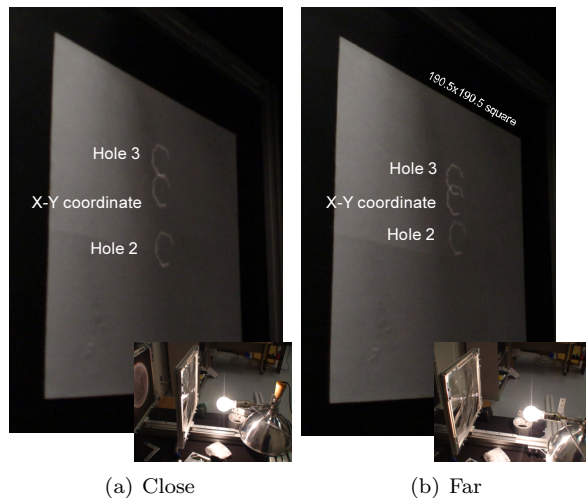


Fig. 7. Images on the screen for (a) closer and (b) farther objects.

searched for correspondences in the vertical direction because the aperture stops were aligned vertically.

The 3D recovery of the filament was successfully achieved as shown in Fig. 8. In this case, we used only the disparity measured between the center and the lower images, not the upper images. The depths of points were computed using (1), and the other coordinates were directly obtained from the center image, which is the same image captured by a conventional telecentric lens.

In summary, we propose a new method to extract 3D information using a telecentric lens, by placing an additional aperture stop on the focal plane along with the stop at the focal point. We investigate the structure of the proposed system and its epipolar geometry that all the correspondences are placed on lines parallel to the direction of the two aperture stops. In addition, we show that, unlike a conventional stereo system, the disparity obtained by the proposed system is linearly proportional to the depth of a scene point. Three dimensional reconstruction of a scene is straightforward and intuitive because the proposed system inherits the benefits of the conventional telecentric lens. Finally, we designed a sim-

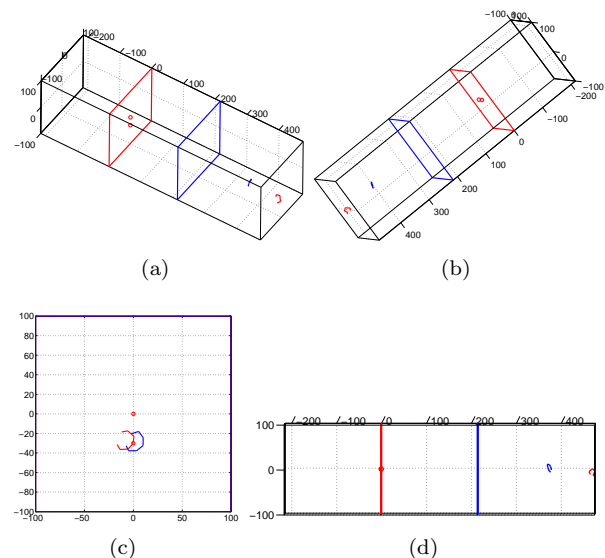


Fig. 8. Reconstruction of the filament using the proposed system. In these figures, the locations of a lens (blue), an aperture plane (red) and a screen (black) are shown, as well as the reconstructed filament in closer (blue) and farther (red) locations.

ple prototype of the proposed system using a Fresnel lens, providing promising 3D reconstruction results.

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