PANORAMIC PROJECTION SYSTEM USING A PANORAMIC ANNULAR LENS

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ABSTRACT

This paper demonstrates the feasibility of using a single projector, equipped with a panoramic annular lens (PAL), to project images onto a cylindrical screen surrounding the projector. The approach could be used to produce real-time, continuous images of objects completely surrounding the initial recording system and may be used in the field of experimental mechanics for tasks ranging from visual inspection and stereoscopic imaging to the interpretation and diagnostic analyses of holographic, speckle, and moiré patterns.

The steps taken to design the panoramic projection system are described and a prototype is constructed along with a compatible recording system. The recording system is used to capture annular images and experiments are conducted to test the prototype, verify analytical arguments, and quantify design parameters.

INTRODUCTION

In recent years, a number of attempts have been made to acquire and project panoramic images for applications ranging from entertainment to inspection and measurement. Prior art imaging systems generally rely on a standard camera and lens system to record image data over a limited field of view. Panoramic data is typically acquired by scanning the surroundings by using a single camera, or, multiple cameras to capture different portions of the scene. The scanning approach precludes the possibility of recording real-time, continuous images making it impossible to capture highly dynamic events. Since many different images must be combined to produce a panoramic image of the objects that originally surrounded the recording system, the presentation of a panoramic image typically requires computational manipulation and/or intricate projection schemes.

The technology underlying panoramic imagery has recently progressed primarily due the advances in computers. Current technology involving the acquisition and projection of panoramic images relies heavily on software algorithms to stitch multiple images together that were acquired either from multiple cameras or by using a single camera to scan the surroundings. While advances in such software have been steady: in image compression to reduce the necessary computing power and available memory required, there have been very few changes of late to the hardware for acquiring panoramic images. And, although some panoramic images have been recorded in real time, very few efforts have been made to project them.

Using multiple high-resolution cameras to accomplish this goal could be cost prohibitive and the approach would require sophisticated algorithms to properly stitch several images without alignment errors due to the inherent discontinuity in the acquisition method. Scanning the surroundings with a single camera requires an expensive and intricate mechanized scheme to provide image stabilization and prevent smear. This approach also relies on stitching the multiple frames acquired from the scan and conforming the imagery to the desired panoramic projection such as cylindrical, spherical, or cubic.

But the major disadvantage to using multiple cameras or stitching images while scanning is that the process can be time-consuming. There are often artifacts in the final image that come from variable lighting conditions, moving objects, and changes in the camera position. These drawbacks severely limit the potential for acquiring and projecting continuous panoramic images in real time, thereby precluding the observation of dynamic phenomena.

This paper addresses a number of these problems by introducing a conjugate optical system capable of projecting panoramic images acquired through a panoramic annular lens (PAL). The PAL has the ability to capture objects contained within a 360-degree band surrounding it; and, the current work explores the feasibility of projecting PAL images onto a cylindrical viewing screen.

RADIAL METROLOGY AND THE PANORAMIC ANNULAR LENS (PAL)

The project is based on pioneer research conducted in the area of radial metrology [1-4], the process of using panoramic imaging systems for optical inspection and measurement. Ensuing work in this area was based on a panoramic annular lens (PAL) [5].

As shown in Fig. 1, the PAL is a single-element imaging block comprised of three spherical optical surfaces and one flat optical surface. Two of the spherical surfaces are mirrored while the third spherical surface and the flat surface are not.

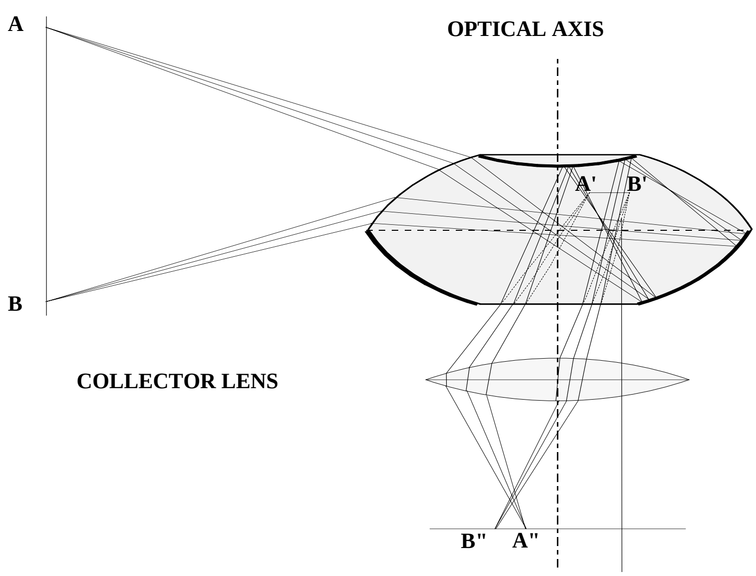

Figure 1. The PAL works based on refraction and reflection.

Rays leaving points A and B are refracted upon contacting the first spherical surface, and reflect off the rear mirrored spherical surface. They travel forward in the lens and strike the front, mirrored spherical surface.

Reflected back, the rays are refracted at the rear flat optical surface and diverge as they exit the lens. The divergent rays leaving the flat optical surface at the back of the PAL can be "back traced" to form virtual images corresponding to points A and B at the points labeled A' and B'. A biconvex lens, labeled as the collector lens, forms real images of these internal points at A" and B". Imaging all points contained within the field of view produces a flat annular image [6] typical of that shown in Fig. 2.

Figure 2. The lens produces an annular image of its surroundings.

As shown in Fig. 3, the optical axis of the PAL is defined by a line perpendicular to the rear flat surface that passes through the centers of curvature of its three spherical surfaces.

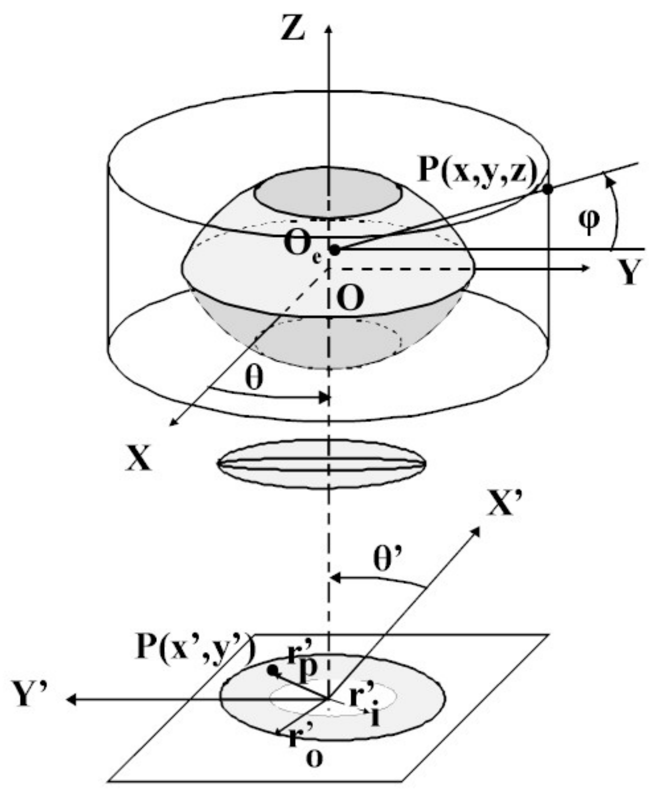

Figure 3. The lens parameters are defined in terms of Cartesian or spherical coordinates.

A longitudinal axis, labeled Z, is chosen to coincide with the optical axis. Two other axes, labeled X and Y, are established in a plane defined by the physical equator of the lens. They are chosen to form a right-handed triad with the longitudinal axis. Cylindrical (r,θ,z) coordinates may also be defined with respect to the origin in real space. The angle θ, measured counterclockwise from X, is called the radial position angle.

At a given θ, all rays in the object space intersect at a common point called the entrance pupil. Point O_e on Fig. 3, for example, corresponds to $\theta = 90^0$. A field angle, ϕ, can be included as one of three spherical coordinates (ρ,ϕ,θ) measured from a local system situated at this point. For $\pi/2 \geq \theta \geq -\pi/2$ and $2\pi \geq \theta \geq 0$, the position coordinates measured relative to the Cartesian coordinate system are

$$\begin{aligned} x &= (o_P + \rho \cos\phi) \cos\theta \\ y &= (o_p + \rho \cos\phi) \sin\theta \\ z &= h_p + \rho \sin\phi \end{aligned} \tag{1}$$

where o_p = 1.342 mm (0.053 in.) and h_p = 6.740 mm (0.265 in.) for the 38.9 mm (1.53 in.) diameter PAL targeted for use in the present study.

Referring again to Fig. 3, the image space is defined by either Cartesian (x',y') or polar (r',θ') coordinates measured from an origin situated at the center of the annulus. Points located on the inner radius, at a radial distance of r_i' in the image plane, correspond to objects viewed at the maximum field angle; points located on the outer radius at r_o', correspond to objects viewed at the minimum field angle.

The field angles corresponding to the points labeled A and B in Fig. 1 are called the upper and lower field angle, respectively. They define the limits on the field of view and are a function of the index of the glass used in the PAL. For a 38 mm (1.496 in.) diameter PAL made from Schott SF14 glass (n = 1.76), $\phi_{upper} = 25^o$ and $\phi_{lower} = -20^o$. When the area between these field angles is rotated around the optical axis through a radial position angle of 2π, a cylinder is described. A collector lens is used to map this continuous field of view onto a flat annular image. But, as proposed herein, the image can be projected around a viewer if a conjugate imaging system is employed.

This 38 mm (1.496 in.) diameter PAL has been characterized in terms of spherical aberration and coma, distortion, image plane curvature, and the modulation transfer function [7]. In general, the acceptance angle varies with the field angle; the amount of spherical aberration is proportional to the acceptance angle. The magnification varies quadratically and image plane curvature is cubic.

Regarding optical recognition, the resolution of the PAL varies from the forward viewing edge to the back viewing edge with an angular resolution of approximately 6 millirads. Even though the PAL is not strictly afocal, objects appear to be in focus from the lens surface to infinity. The transmittance varies less than five percent over the visible light range; however, since the PAL is both refractive and reflective, it does not possess the same performance for all wavelengths.

In radial metrology, the aspect ratio of an area is defined as height divided by width [8]. In real (or object) space, height is measured as the longitudinal distance relative to the optical axis of a lens; width corresponds to the circumferential distance measured around the optical axis. In image space, height is measured as a radial distance relative to the center of an image; width corresponds to a circumferential distance measured around the image center.

When a conventional lens is used for radial metrology, a cylinder, whose inside surface is composed of a uniform grid of squares, is mapped into the image plane as a series of evenly spaced concentric rings representing equally spaced lines drawn around the circumference of the cylinder; radial lines represent the longitudinal lines drawn along the length of the cylinder at constant circumferential positions. Figure 4(a) illustrates that, in the case of the conventional lens, square elements having a real space aspect ratio of unity are mapped to an image comprised of segments that have different image plane aspect ratios. The PAL maps the same uniform grid of squares into the constant aspect ratio polar map illustrated in Fig. 4(b).

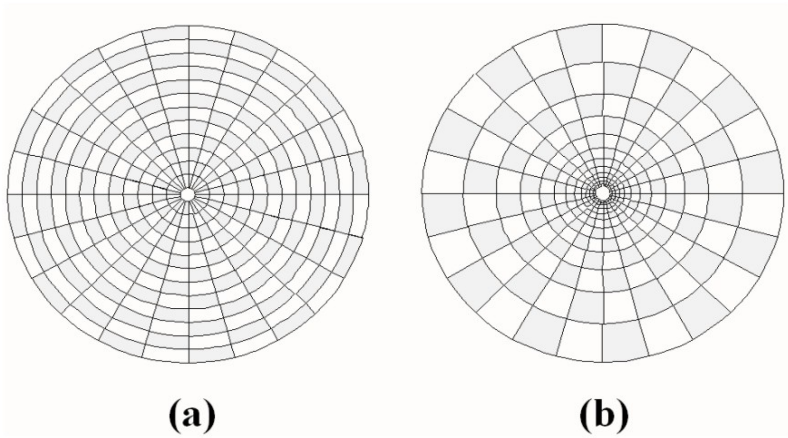

Figure 4. A square grid wrapped around the inside wall of a cylinder becomes (a) a conventional polar map when recorded with a conventional lens; and, (b) a constant aspect ratio polar map when recorded with a PAL.

The polar mapping function has been characterized [6, 8]; the aspect ratio for the 38mm (1.496in) diameter PAL targeted for this study is approximately 0.75. The constant aspect ratio mapping of the PAL leads to higher information density, thereby setting the proposed panoramic viewer apart from any of those that could be constructed with different panoramic optical elements such as aspheric omni-directional mirrors or panoramic refractive optics.

PANORAMIC PROJECTION USING A CONJUGATE OPTICAL SYSTEM

Many studies and designs have been performed to address panoramic imaging and how to obtain a greater than 180-degree to 360-degree field-of-view. Although many images have been recorded in real time through panoramic systems, few attempts have been made to project them around a viewer.

Due to the complexity and cost associated with devices ranging from multi-element fish-eye optics to diamond turned aspheric mirrors, recent efforts have been directed towards software development to generate 360-degree renderings of scenes from multiple images taken from multiple vantage points. Little attention has been paid to the development of real-time acquisition without the need for sophisticated algorithm development. But such considerations are extremely important while moving towards a real-time projection system, and experience with the PAL and radial metrology offer innovative solutions to many of the current and unaddressed issues associated with the design, performance assessment, and production of a panoramic real-time viewer.

One approach to panoramic projection is to employ a conjugate imaging system. The first step is to record a panoramic image. Then, the image is projected onto a cylindrical screen using the same optical train employed to acquire it. Although the conjugate imaging approach could be applied with other panoramic optical elements, the PAL offers distinct advantages due to its unique conformal mapping and afocal-like properties.

The PAL projection system developed herein relies on a rear projection method in which a real image is projected onto the viewing screen. This is accomplished, as illustrated in Fig. 5, by placing the projection system in the center of a cylindrical screen. When a translucent screen is employed, the viewer may view the image from the outside of the cylindrical screen. However, the objects in the field of view will be reversed circumferentially.

The projection system projects the panoramic image by playing a previously recorded PAL image back through the lens. To do this, an optical system is used to place the annular image inside the lens at its “normal” virtual image location (A’ and B’ in Fig. 1). For the purposes of describing the system, the location of the virtual image will be subsequently referred to as the PAL object plane.

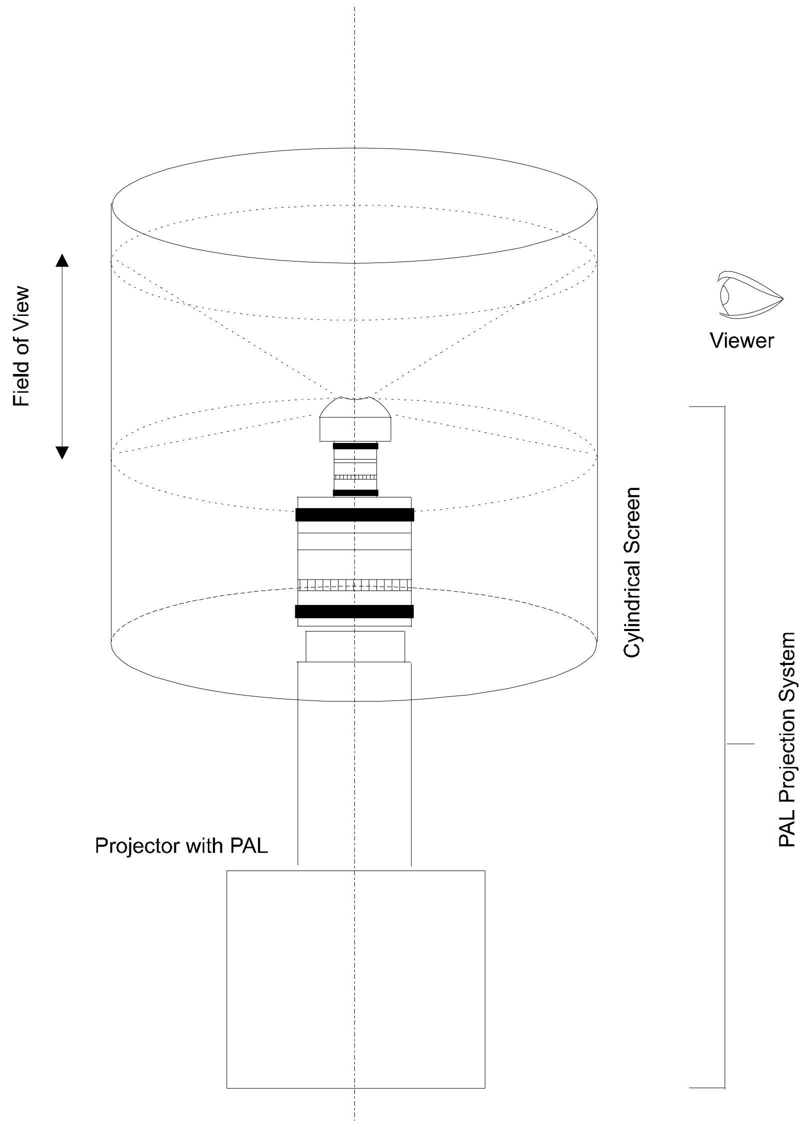

Figure 5. PAL projection system.

As illustrated in Figure 6, the PAL projection system includes the same basic components as a conventional projection system. The panoramic projection system is divided into two major sub-systems: the illumination sub-system and the imaging sub-system. The illumination sub-system consists of a light source with a reflector, a heat absorber, and a condenser lens. The imaging sub-system consists of the film to be projected, a projection optics sub-system, and a cylindrical viewing screen. The projection optics sub-system consists of a transfer lens and a PAL.

The light source is the main component of the illumination sub-system. The brightness of the projected image depends strongly on the brightness of the light source. A reflector is positioned behind the light source to enlarge the solid angle collected by the imaging sub-system and increase the illumination obtained.

A heat absorber is used to protect components from excessive heat created by the light source. The absorber is placed immediately before the condenser lens to absorb heat while transmitting light.

The condenser lens images the light source onto the entrance pupil of the projection optics sub-system, and several steps had to be taken to achieve a uniform illumination. Following the Koehler illumination method [9], the image size of the light source must be adjusted to be larger than the size of entrance pupil of the projection optics sub-system. The film to be projected must also be placed as close as possible to the condenser lens.

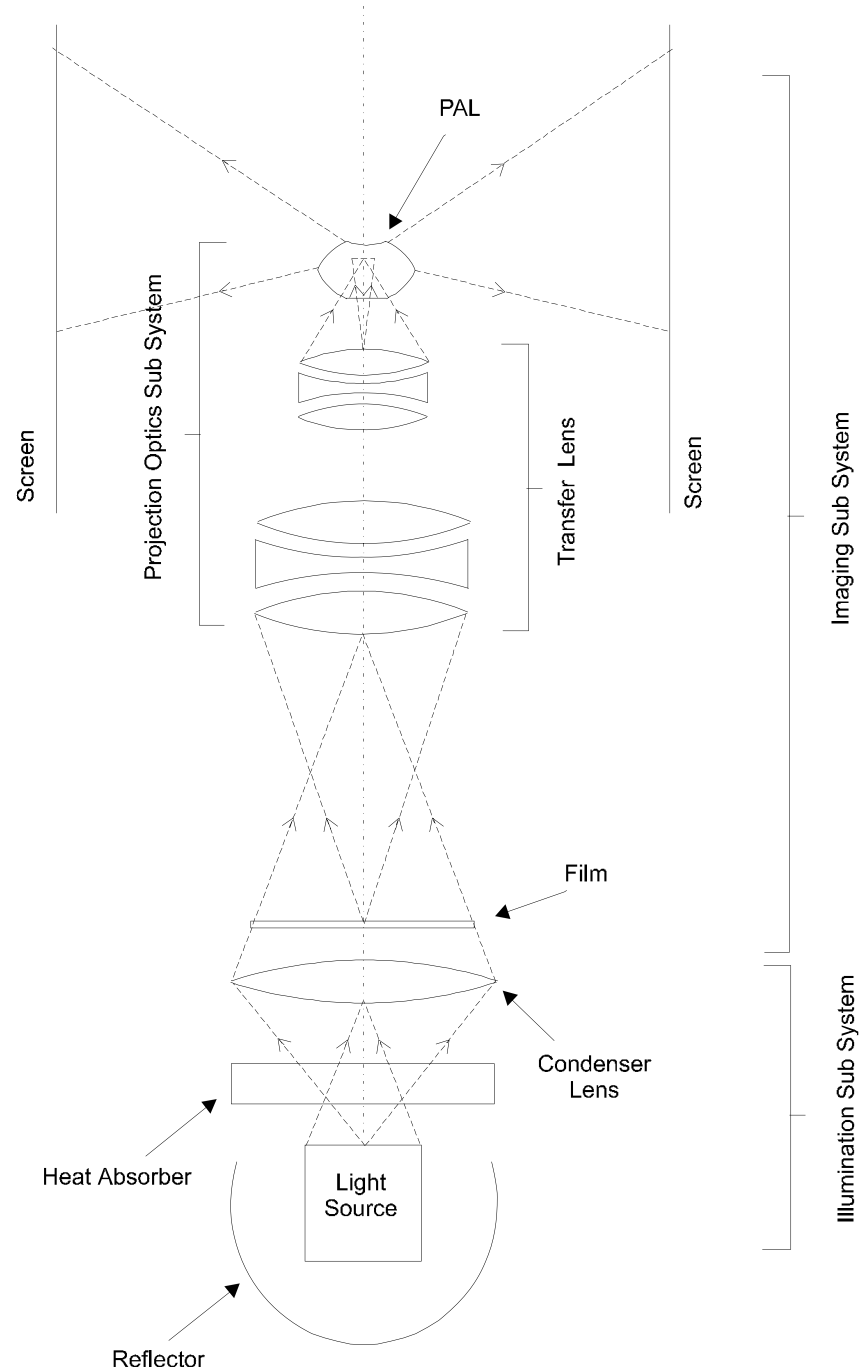

Figure 6. Basic design of a PAL projection system.

A transfer lens must be designed to project the objects contained on the film into the PAL object plane. The focal length of the transfer lens depends on the components included in the illumination sub-system as well as the object size. For the conjugate approach to work, the image size obtained from the transfer lens has to match the object size required by the PAL used to project the image.

The PAL is placed after the transfer lens. Thus, the image from the transfer lens becomes the virtual object for the PAL. Since the PAL is not strictly afocal, the required position for the virtual object plane for the PAL depends on the screen diameter. For a larger diameter screen, the image needs to be positioned further from the transfer lens. Consequently, the position of the projection optics sub-system was made adjustable to enable the image to be projected onto screens of different diameters.

A translucent screen was used, since the image is viewed by rear projection. The screen is aligned such that its axis is coincident with the axis of the projection optics sub-system. This alignment is critical, since deviations create anomalies in the sizes and shapes of the objects projected.

VALIDATION AND EXPERIMENTAL TESTING

A prototype system was designed to illustrate the conjugate imaging approach. This was done by modify a Kodak Ektagraphic II ATS projector from a conventional projection system to a panoramic projection system simply by changing the projection lens. The existing illumination sub-system placed constraints on the design which focused on the development of the panoramic projection system.

In the Kodak Ektagraphic II ATS Projector, a 31 mm diameter light source is placed 112 mm behind a condenser having a focal length of 60 mm. Thin lens design formulas reveal that the image of the light source is formed at 129 mm to the right of the condenser lens. The entrance pupil of the projection optics sub-system had to be located approximately at this position. In the projector, an annular image having an outer diameter of 22 mm was located at a distance of 23 mm to the right of the condenser lens. This knowledge was used to establish the focal length of the transfer lens at 44 mm.

The required transfer lens was built by combining two compound lenses of different focal lengths: a 35 mm lens and a 16 mm lens. In order to obtain the required 44 mm focal length, the distance between the principal planes of these lenses was set at 38.4 mm. The 35 mm focal length lens was equipped with an adjustable diaphragm to change the f-number. The distance between the transfer lens and the film was made adjustable so that the system could be used to project images onto screens of different diameters. The 38-mm diameter PAL was mounted to the 16 mm focal length lens. Figure 7 shows a photograph of the prototype.

Figure 7. Prototype PAL projection system.

A number of annular images were recorded on 35-mm film prior to testing the PAL projection system. The first set of images was recorded in the laboratory by placing a test strip on the inner wall of a glass cylinder. Figure 8 shows a schematic diagram of the experimental setup. The optical axis of the PAL recording system was positioned parallel to the longitudinal axis of the cylinder; the system was centered within the cylinder. Since the acceptance angle of the PAL is relatively small, the test strip was back-lighted using a circular, 40-Watt fluorescent bulb positioned outside the cylinder.

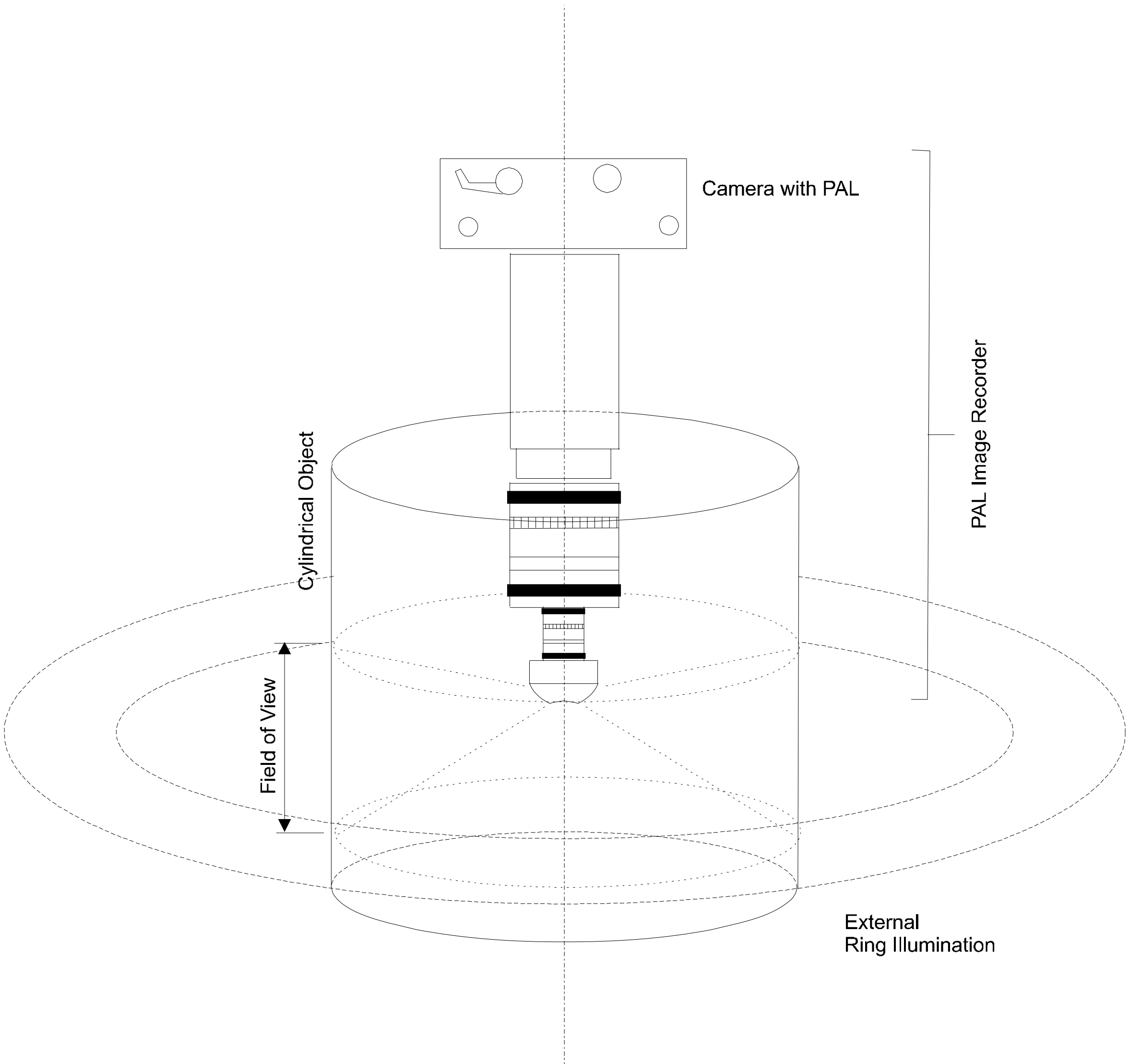

Figure 8. Schematic diagram of the experimental setup for test pattern recording.

The PAL recording system itself consisted of a Nikon camera body equipped with the same optical train used in the panoramic projection system. Figure 9 shows a photograph of this configuration.

As discussed previously, the PAL captures a virtual image that is converted into a real image by the transfer lens. The real image is recorded on the film plane located in the body of the camera. A diaphragm in the transfer lens controls the f-number of the system, and the shutter speed of the camera is adjustable. These parameters allowed annular images to be captured under different exposure conditions. The annular image in the focal plane of the camera had an outer diameter equal to 22 mm and an inner diameter of 8.4 mm.

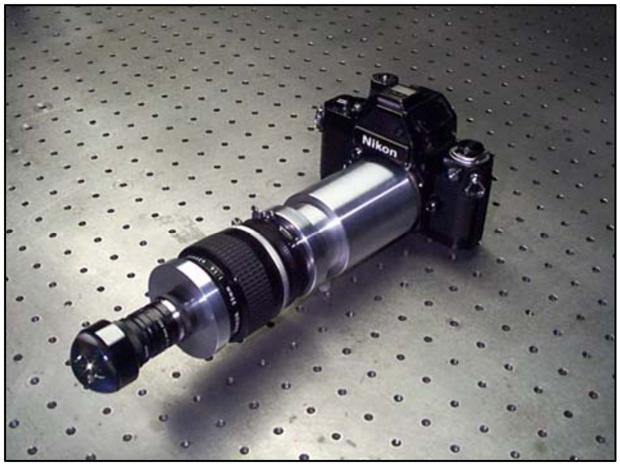

Figure 9. Prototype PAL recording system.

A second set of images was recorded by taking a number of photographs outdoors under partly cloudy conditions. An image recorded at a shutter speed of 1/15 second, with an f-number of 5.6, was used to test the PAL projection system.

The annular images acquired from the recording system were projected using the PAL projection system. This was accomplished by placing each one in the film plane of the projection system with the center of the image located on the optical axis. The diaphragm in the transfer lens was used to adjust the f-number of the projector to obtain sufficient brightness and good image quality. Figure 10 shows a photograph of the projection system and a projected image.

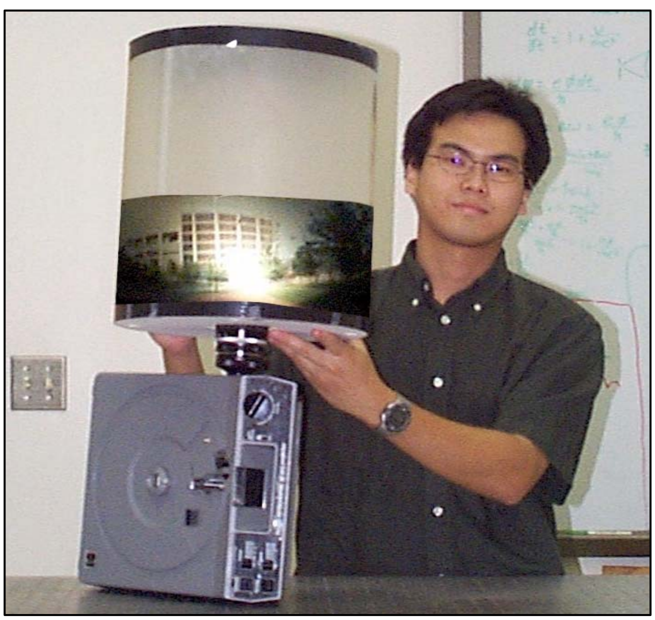

Figure 10. Panoramic projector with circular screen and projected image.

CONCLUSION

The panoramic projection system developed herein relies on a PAL and a single projector to create a real image on a cylindrical screen. Since the image is continuous, there is no need to stitch images together or combine different projections. This potentially lowers cost and eliminates the need for critical alignment of separate image segments. The most significant advantage of the approach is that it can be used to record and project panoramic images in real time.

The prototype relies on a 300-Watt light source to project images onto a screen of relatively small diameter. Slight modifications could be made to project larger and brighter images. Steps could also be taken to correct aberrations for application-specific systems allowing them to be used for commercial, entertainment, or computational purposes. The projector could be featured in a trade show display, for example, or used in conjunction with a PC at home or at the office to view real-time video. The system could also be used to as a light guide to facilitate operations, such as optical computing.

The possibility of using a front projection method could also be explored. In this case, the viewer could sit within the screen to view their surroundings. This could allow a user to remotely monitor traffic flow at a busy intersection or to conduct a surgical procedure with the help of the new tools being developed in the area of virtual reality.

One of the most exciting possibilities is to adapt the optics for use with a digital projector. The applications for this technology are endless and, if successfully developed, may change the world's perspective.

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