

Endoscopic inspection using a panoramic annular lens

by

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ABSTRACT

Endoscopy is a technique for imaging the inner part of a volume or cavity. Such techniques have applications in many areas, such as medicine, civil engineering, and aerospace; indeed, anywhere tubes and pipes are involved. The present paper discusses a method of endoscopy which utilizes a unique panoramic annular lens to obtain a flat two-dimensional annular image of the 360 degree surround of the optical system. Although the distortions involved in the optical mapping to produce such an image are not very severe, and the images can be interpreted by inspection, computer algorithms are introduced to linearize the images so as to simplify their interpretation.

1. BACKGROUND

Various physical measurements can be made on pipes, tubes, and boreholes subjected to static and/or dynamic deformation and rigid body motions. Most of this work is conducted by destructive means (by removing material, causing the structure to fail, etc.), or by applying nondestructive methods to the outside of the structural component. Only a small fraction of these measurements rely on endoscopic inspection: a technique for imaging the inner part of a volume, or cavity. From the early work of researchers such as Mangin¹ in 1878 to develop suitable optical instruments up to recent times, efforts to stress analyze interior cavities through endoscopes have met with only limited success.

Ideally, a device for making measurements of the inner surface of a cavity should be rugged, compact, and capable of obtaining an unobstructed, complete, and comprehensive image of the cavity space in every direction. Unfortunately, it is virtually impossible to develop a practical device capable of recording such a sphere of vision. However, many cavities can be regarded as cylindrical rather than spherical volumes, and visual information about such cavities can be mapped by the panoramic annular lens into a flat annular image, creating a 2-D representation of the 3-D cylindrical surface.

Since the time of Mangin, numerous devices to enable endoscopic viewing have been patented.² These endeavors can be divided into two main groups; those in which the imaging device or a part of it is rotated around its axis to scan the interior, and those which utilize combinations of optical elements to obtain a single panoramic view of the interior. These optical elements may have several refracting/reflecting parts with collinear optical axes or may consist of a single block having several refracting and reflecting surfaces. Unfortunately, these compound systems are often difficult to manufacture if high quality panoramic images are needed. Consequently, most endoscopic inspection systems use scanning techniques.^{3,4} Of course these systems also have disadvantages: beside the need for a rotating mechanism, no simultaneous recording of the entire space is possible.

Many of the drawbacks of compound and scanning systems as listed above were addressed in the development of a panoramic annular lens system introduced by some of the authors in a recent paper⁵ and described in the following section.

2. PANORAMIC ANNULAR LENS

The panoramic annular lens (PAL) consists of a single piece of glass with spherical surfaces that produces a flat annular image of the entire 360 degree surround of the optical axis of the lens with a field of view extending from about 50 degrees off-axis to about 100 degrees off-axis, and which has a depth of field extending from the surface of the PAL to infinity. A virtual annular-shaped image of the surroundings of the lens is formed inside the lens; this virtual image can be imaged onto a film or sensor by the use of a transfer lens. Fig. 1 shows the geometric structure of the PAL. The thick lines indicate reflecting surfaces.

If a cavity can be regarded as a cylindrical rather than a spherical volume, the image information can be transformed, using stretching methods, onto a flat surface creating a 2-D representation of the 3-D cylindrical surface. This phenomenon called Flat Cylinder

Perspective (FCP) forms the basis for the image produced by a panoramic annular lens.⁶ In an 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).^{6,7} Fig. 2 shows a diagram representing flat cylindrical perspective and shows the limiting angles involved in determining the field of view. Obviously, it would be desirable to make α large and β small, so as to maximize the viewed surface, but restrictions are imposed on the values of these parameters by the limited range of values of the index of refraction that can be obtained in commercially available glasses.

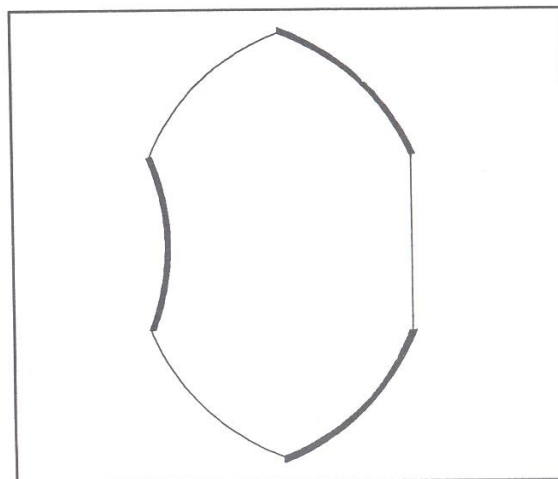


Fig. 1 Physical shape of a panoramic annular lens (PAL).

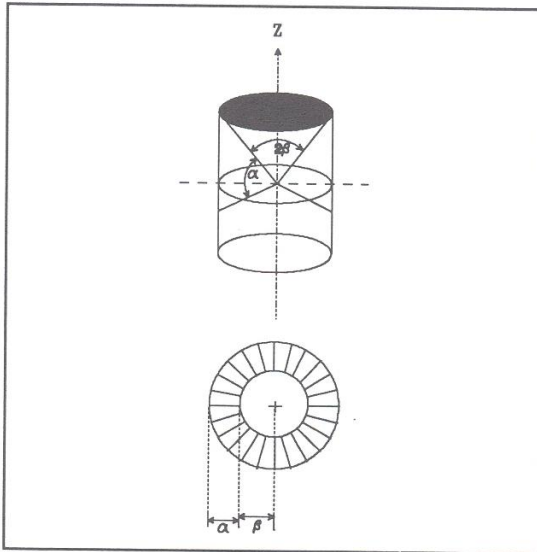


Fig. 2 The PAL lens forms an image using flat cylindrical perspective.

The width of the annular FCP image corresponds to the size of the acceptance angle α , and each concentric ring in the image plane is the locus of points recorded at a fixed angle to the optical axis. The lens produces an annular FCP image where the width of the annular image corresponds to the vertical viewing angle, and where each concentric ring in the image plane is the loci of points recorded at a constant horizontal field angle.⁷ A ray diagram showing how the rays from the cavity wall traverse the lens and form a virtual image inside the PAL itself is shown in Fig. 3. Fig. 4 shows the use of a transfer lens to image the internal virtual annular-shaped image onto an external film or sensor.

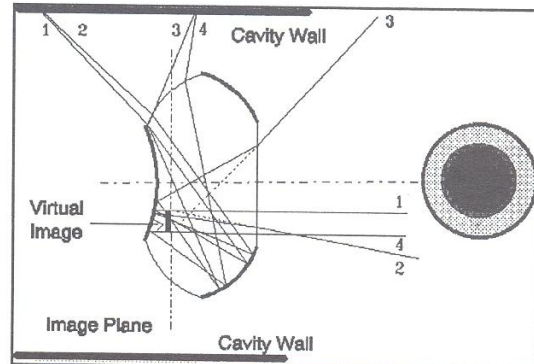


Fig. 3 Ray diagram for a panoramic annular lens.

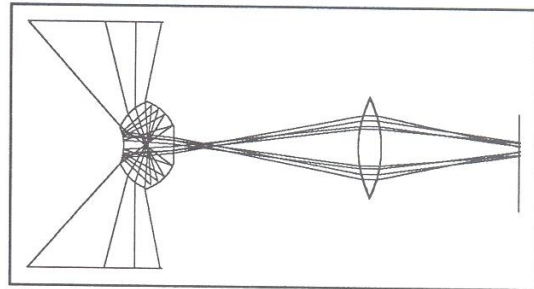


Fig. 4 Use of a transfer lens to produce a real annular image.

3. LINEARIZATION OF AN ANNULAR IMAGE

Direct visual interpretation of a PAL image is sometimes confusing for the unskilled observer. With this in mind, an algorithm was developed to allow the annular shaped images to be linearized for viewing and measuring purposes. It must be recognized that there is no way to present a nonrectangular image in a rectangular format without distortion. This is essentially the same problem as making a flat map of a round globe. However, the type of distortion introduced can be chosen and controlled by the choice of mapping scheme that is used (equal maximal dimensions, equal areas, etc.). The mapping used here maintains equal maximal dimensions by 'rolling' the annular image along its outer circumference and moving all the pixels between the contact point and the center of the image to a vertical line in the final rectangular image.

In order to test the linearization routines, a test drawing was prepared and placed around the interior wall of a pipe. This test drawing contained a different pattern, *i.e.*, diamonds, squares, checkerboard, and concentric circles, in each quadrant of the cavity wall. Referring to Fig. 5, which shows the image obtained through the PAL, it can be seen that the distortion introduced by the FCP mapping is not severe, and the image is clearly recognizable. However, if it is desired to 'straighten out' the image, two stages of linearization are needed: (1) tangential linearization and (2) radial linearization. In the tangential linearization, a wedge-shaped portion of the annular image of the inside of the pipe is converted into a rectangular section. Next, because the annular image is not linear in the radial direction, a vertical stretching of the rectangular image is required; this second process is radial linearization.

The first step in linearizing the images obtained from the panoramic annular lens is to specify the desired region of the annular image that is to be straightened. This is done by entering four (x,y) locations into the computer. The first two points should be on the outer circumference of the image and specify the end points of the region of interest. The third point must be on the same circumference and allows the computer to calculate the radius appropriate to the image being examined and also specifies which of the two possible segments between the first two points is desired. The last point is chosen anywhere along the inner circumference and allows the machine to determine the image height. The machine now knows the entire segment that is desired and can proceed to straighten it out. Although arbitrary regions of the annulus can be selected, in this paper it will be assumed that a quadrant of the entire image has been chosen, in particular, the quadrant containing the pattern of concentric circles.

First the center location of the annulus is calculated (this center point need not be in the portion of the image which is stored in the computer), and then the height and width of the output rectangular image are determined in units of pixels. The final width of the image will be equal to the length in pixels of the outer circumference of the selected segment. Fig. 6 illustrates how samples (shown as 'o's) in the annular image are mapped into a rectangular array. After the outer radial length is selected at one end of the specified region, the radial angle is incremented until the other end of the specified region is reached; then the radius is decremented and the process repeated. After this linearization, the number of columns in the image, which is determined by the angular increment used, is adjusted, by averaging, to have the same number as the outer arc length of the selected wedge. Next the vertical height of the rectangle is then determined by calibrating the system. This calibration

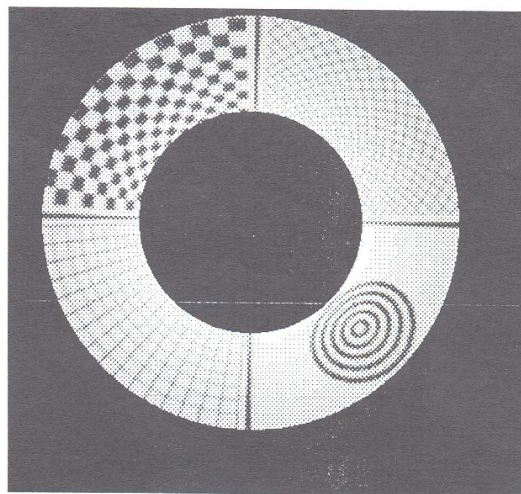


Fig. 5 The test pattern as imaged by the PAL.

is accomplished by covering the interior cavity wall with a grid. Since the vertical and horizontal lines of the grid have the same spacing on the walls of the cavity, they should be equally spaced on the final linearized image. The spacing between vertical lines is taken as a reference and the spacing of the horizontal lines in the rectangular image obtained after tangential linearization is adjusted to obtain such a separation. Fig. 7 shows the mapping involved between the desired spacing or row number, and the measured radial spacing of the PAL image, and a least-squares-fit equation for mapping vertical positions in the linearized image.

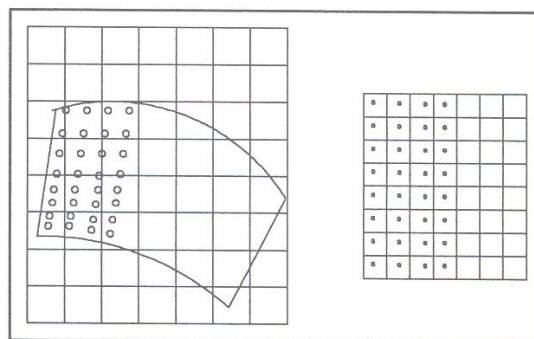


Fig. 6 Mapping ρ, θ polar coordinates into x, y cartesian coordinates.

Since we are magnifying part of the source image by performing this radial linearization, a one-to-one mapping of source to destination pixels is not guaranteed. When an image is magnified, one pixel in the source image may be mapped to many pixels in the destination image. This source to destination pixel mapping is done from the perspective of the destination image.⁸ This reverse mapping is required to guarantee that every pixel in the destination image is given a value. Without the one-to-one correspondence between source and destination pixels it cannot be guaranteed that some source pixel will be mapped into each and every destination pixel. If there were no reverse mapping then there would be pixels that are not given a pixel value. These voids would degrade the appearance of the destination image.

Reverse mapping traverses the destination image space a pixel at a time and uses the transformation function to determine which pixel of the source image would be involved in producing the destination pixel.

However, reverse pixel mapping creates a second problem. There will be fractional pixel addresses. These occur when the source image pixel that contributes to a destination pixel's value is calculated. To deal with these fractional addresses an interpolation is performed to calculate a new value for some point with a non-integer (x, y) location that is situated between other points of known value. The corner points of known value that surround the point being calculated ('P', in our case) have a larger impact on the value of the

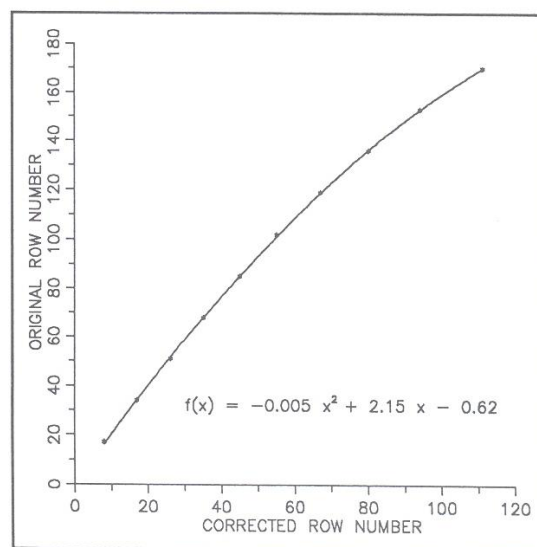


Fig. 7 Least squares fit to experimental data for PAL image linearization.

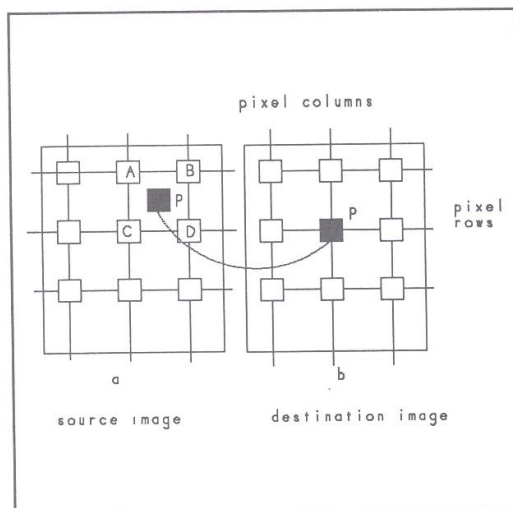


Fig. 8 Reverse mapping from final image to source image.

calculated point than points further away. Assuming that the points are close together and that the intensity does not change rapidly with position allows the use of simple linear interpolation.

In Fig. 8, a pixel has a non-integer address. The intensity of the pixel [P] with non-integral address values of (x,y) is derived from the intensities of pixels [A],[B],[C], and [D] according to their relative distances from the calculated address of the transformed pixel. A two-dimensional interpolation is performed by making three linear interpolations of intensity values as shown in Fig. 9. The grey scale values of [A] and [B] are interpolated first, and then the grey scale values of [C] and [D]. Using these two interpolated values as endpoints, the final result to be used as the grey scale value is interpolated linearly in the vertical direction.

Fig. 10 shows the final image obtained after applying both tangential and radial linearizations.

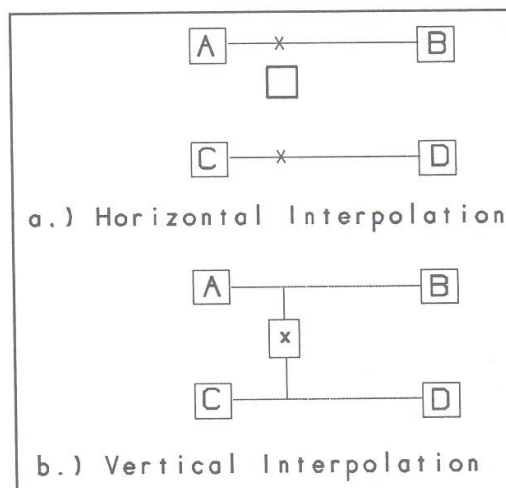


Fig. 9 Interpolation of intensity values for non-integer coordinates.



Fig. 10 Linearized image of one quadrant of the test pattern.

4. ACKNOWLEDGMENTS

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