Hemispherical Photographs Used for Mapping Confined Spaces

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Abstract

This paper presents two methods for using fisheye photographs for mapping confined areas. The first approach is intended for relatively flat objects, observed at very close range, and consists of producing a rectified view from a fisheye photograph. After scanning and correcting the spherical distortions present in the original image, a simple projective transformation creates a constant scale image from which two-dimensional (2D) data can be extracted. The second method aims at recovering three-dimensional data from two stereo fisheye photographs. This method also involves the same image correction for spherical distortions, but the two resulting perspective images are afterwards analyzed utilizing stereovision in a digital photogrammetric workstation. Practical experiments, conducted with a 35-mm camera equipped with a fisheye lens, demonstrate the applicability and feasibility of the two softcopy photogrammetry methods in the context of mapping electric distribution wells.

Introduction

Measuring or mapping confined areas, such as underground cable access wells, has always represented a practical challenge. In the present context, a confined area might be viewed as a room having a floor area of about 2m by 2m. The use of conventional surveying instruments like theodolites and electronic distance measurement apparatus is not recommended for mapping these small spaces. The minimum distance that a theodolite can accommodate is generally around two metres. Furthermore, the manipulation of a prism for distance measurements is somewhat problematic in such spaces. Finally, the space required to set up and operate these instruments makes their utilization practically impossible. Similarly, conventional photogrammetric operations involving metric cameras with normal angle lenses do not offer a practical solution. Because of the short object distance and the limited camera field angle, an excessive number of photographs would have to be taken to cover the whole subject, which would significantly decrease the effectiveness of the photogrammetric approach.

A camera equipped with a hemispherical lens, or fisheye lens, may represent the best acquisition tool. With a 180-degree angular field, the fisheye lens has the capability to record a very large amount of information of an object placed at very close range. Paradoxically, the photogrammetric literature shows only a few applications of this type of lens since its first introduction in 1924 (Hill, 1924). Actually, fisheye lenses are more frequently used for photographic special effects, and, perhaps, the large amount of distortion has discouraged many photogrammetrists. Nevertheless, some pioneers have presented interesting applications in different domains such as forestry, the study of plant canopies (Rich, 1990), geodesy, or to produce a site obstruction diagram for future GPS missions (Colcord, 1989). In these applications, as well as others (Richardson, 1992; Weigian *et al.*, 1992), an analytical approach is always used to recover some metric data directly from the distorted images. The main limitations of this solution are the impossibility of using conventional softcopy photogrammetry packages and, more importantly, the fact that fisheye images do not permit stereovision.

Here, fisheye lens calibration and practical tests are conducted using a softcopy photogrammetric approach. Consequently, the first step is to digitize the fisheye photographs using a standard scanner. Corrections of the spherical distortion are then applied in order to create images directly usable as input for common softcopy photogrammetric processes. When the distortions are corrected, the resulting synthetic image is similar to an image taken by a camera having a very short principal distance. It will be demonstrated that such an image either can be rectified to create a constant scale image, when a relatively flat object is considered, or can be used directly to reconstruct a stereoscopic model. However, because fisheye lenses are much more complicated to manufacture than conventional lenses, the distortions observed do not perfectly match their theoretical values which leads to a lower accuracy in comparison to the usual photogrammetric standards. Nevertheless, for many applications, fisheye photographs can produce usable solutions to practical problems, as is described in this paper.

Fisheye Geometry

A typical fisheye lens construction is shown in Figure 1. The multiple optical components, characterized by a 180-degree field angle, can be simply represented by an ideal hemispherical lens as illustrated in the central left part of Figure 2. According to the diagram, a light ray from a point (P) hitting the lens from a zenith angle (ζ) is deviated and creates an image at location (p). The radius of the hemisphere is represented by (R) and the radial distance of the image point from the principal point, by (r). Depending on the amount of deviation of the ray or, indirectly, on the radial distance, four different types of projection characterize fisheye lenses (Herbert, 1987). They are

- polar : $r = 2R\zeta/\pi$
- orthographic : $r = R \sin(\zeta)$

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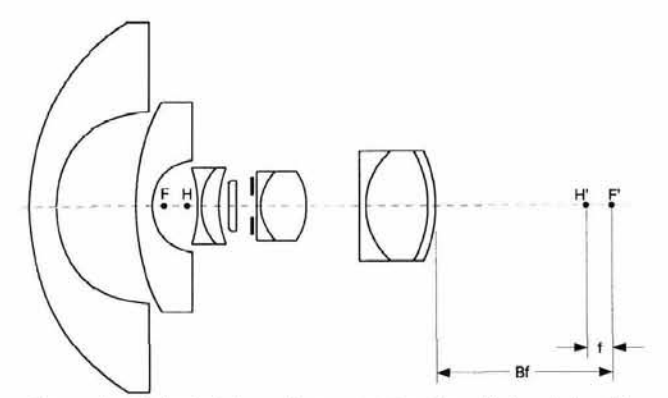

Figure 1. Typical fisheye lens construction (f: focal length, Bf: back focus, H and H': principal points, F and F': focal points).

- Lambert's equal area : $r = (2R/\sqrt{2}) \sin(\zeta/2)$
- stereographic equal angle: $r = R \tan(\zeta/2)$

Most lenses currently available on the market are designed to produce a polar projection (e.g., Nikon 8-mm *f*/2.8, Canon 7.5-mm *f*/5.6, and Sigma 15-mm *f*/2.8).

Fisheye Lens Calibration

In this paper, correction of fisheye lens distortion is accomplished by the construction of an image situated on the tangent plane of the hemispherical lens at the intersection of the optical axis. With reference to Figure 2, the corrected position (p') of a point (P) is a function of the zenith angle (ζ), the hemisphere radius (R), and the position of the principal point (O). In order to correct a fisheye image, these last two quantities (R and O) have to be estimated. Because R and O might vary slightly as a function of focus and aperture settings, the calibration should be done under conditions similar to those during data acquisition.

The position of the principal point (O) can be determined by mounting a fisheye lens on a rotating optical bench, as described in Herbert (1987). The basic principle of this analog method relies on the fact that a circular target creates a circular image when located exactly on the optical axis of the lens. A series of photographs of a circular target, positioned in the vicinity of the optical axis, are taken. Then, for each photograph, the axes of the elliptic image projected by the lens are measured. When these axes are practically equal, meaning that the target was located on the optical axis, the center of the circular image corresponds to the principal point. An alternative solution, proposed in this paper, is to simply assume that the principal point corresponds to the circular image center. Practically, the localization of this center point, from the measurement of a series of image points on the circumference, can be difficult. Indeed, some lenses (e.g., Sigma 15-mm *f*/2.8) produce circular images slightly exceeding the rectangular 35-mm film format. Even when the circular image fits into the film format, the poor resolution near the circumference of the fisheye image makes the measurement very imprecise. For these reasons, the use of a cylindrical lens hood is suggested. This lens hood, usually provided with a fisheye lens, restrains the field angle, which leads to circular images with less spherical distortions and with a sharper definition. Fitting directly on the lens casing, it is assumed that the center of the lens hood lies on the optical axis and that the equivalent image point corresponds to the principal point. If the position (x,y) of at least three image points of the lens hood is measured, the circle center (h,k) is calculated using the circle equation: $rh^2 = (x - h)^2 + (y - k)^2$, where rh is the hood radius. Because the image coordinates are expressed in terms of pixels, the principal point location will be determined in the same units. If more than three points are measured, a circle fitting approach must be performed. Similar to the straight line fitting method (see, for example, Kreyszig (1979), the three parameters (h, k, and rh) can be estimated by minimizing the sum of squares of the residuals obtained by the circle equation. The lens hood radius (rh) is not a calibration parameter and has no further use.

With non-metric cameras, the image corners are usually considered as fiducial marks. However, the image corners are not visible when pictures are taken with the lens hood. Indeed, because of the lens hood's dark color, the outer part of the circular image is practically not exposed, making it impossible to find the image corners. To avoid this problem, a white adhesive tape is temporarily placed on the inner side of the lens hood. In this way, the principal point location can be defined with respect to the image corners.

The second calibration step is related to the determination of the hemispherical lens radius (R). Theoretically, this parameter could be evaluated by measuring the radius of the circular fisheye image (without the lens hood). But as already stated, the operation is practically impossible because of the film format and the poor image resolution at the circumference. To overcome this situation, an indirect method is suggested.

As illustrated in the central left part of Figure 2, and explained in detail in the next section, the spherical distortion correction can be viewed as the construction of an equivalent image located on the tangent plane of a hemispherical lens. In this way, the corrected position of any fisheye points

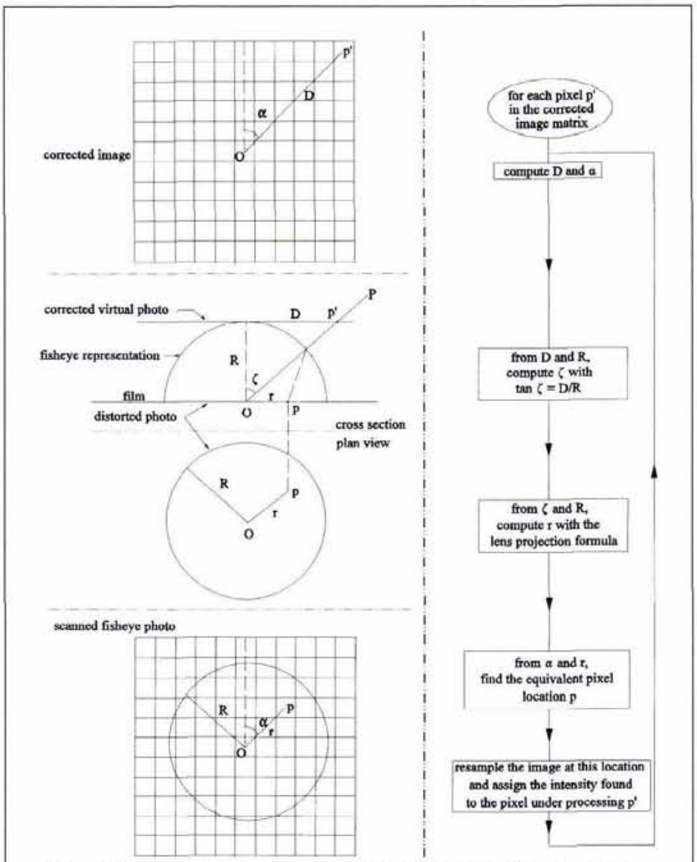

Figure 2. Diagrammatic representation of a fisheye lens projection and correction flow chart.

can be determined using the lens projection equation provided by the manufacturer. The hypothesis upheld by the proposed calibration method is the following. The best estimation of the fisheye lens radius (R) is obtained when this value produces the best correction for spherical distortions. To properly assess the quality of the correction process, a fisheye photograph of an object with several rectilinear features is required. On the digitized fisheye photograph, a set of well distributed features, which appear as curves, is selected and the positions of three points are measured on each feature. The corrected positions of the three points are then determined by using a first approximation of the lens radius (R), which is equivalent to half the image width. As opposed to the process described in the next section, the goal here is not to produce a corrected image but only to find the corrected position of the three key points. The process begins at the original image level (see left side of Figure 2) and ends at the corrected image stage. It includes the following steps: determination of the radial distance (r) and the azimuth (α) of a point (p), determination of the zenith angle (ζ) from the lens projection formula, and determination of the radial distance (D) which provides, with (α), the corrected image position (p') of the point (p). If the corrections of the spherical distortions were perfect, the three points taken on each feature would be collinear and the cosine of the angle defined at the middle point would be equal to -1. The overall image correction can be evaluated by taking into account the cosine angle (θ) for each rectilinear feature. Practically, this is accomplished by calculating the sum of the values $(cos\theta - 1)^2$. Then, the R value is incremented by one pixel and the process is repeated. This iterative process ends when R reaches a value equivalent to one-and-a-half image widths. The best estimate for the radius (R) is the one that produces the smallest sum. As for the position of the principal point, the radius of the hemisphere does not vary from one exposure to another if the focus and the aperture are not modified.

Fisheye Image Correction

Once a fisheye lens has been calibrated, a simple algorithm can be used to correct the spherical distortions of any photograph taken with this lens. In digital photogrammetry, image resampling and correction are usually pursued in an indirect approach. The algorithm assigns, to a pixel on the corrected image, the intensity of an equivalent pixel found on the distorted image. This correction strategy eliminates the situation which is frequently encountered when a direct approach is adopted, of having unassigned pixels in the corrected image matrix.

A computer program for the correction of fisheye images must go through the following series of steps. First, the corrected image dimensions have to be determined. Because fisheye lenses have a 180-degree field angle, the virtual image, as illustrated in Figure 2, would be of infinite dimensions. A field angle must thus be arbitrarily fixed. Then, the image dimensions can be calculated using this angle and the hemisphere radius (R). If the radius has been determined in terms of pixels during the calibration process, the image format is directly obtained in pixels. During the resampling process, a scale factor can be introduced which produces an effect equivalent to setting the projection plane (virtual image) at a different height with respect to the distorted image plane (Figure 2). Afterwards, each pixel on the corrected image matrix is treated as shown in the right side of Figure 2. The distance (D) between the pixel under processing (p') and the principal point location (O) on the corrected image is calculated. From an arbitrary direction, for example the column, the azimuth angle (α) is also computed. To find its equivalent pixel on the distorted image, the zenith angle is determined with the equation: $\zeta = \tan^{-1}(D/R)$. From this angle and the fisheye lens projection formula (see section on fisheye geometry), the radial distance (r) is determined. Most photographic lenses produce very little variation in azimuth of the incident ray (Herbert, 1987). Thus, the azimuth (α), calculated on the corrected image, can be applied to find the equivalent distorted position in polar coordinates. From this position, different resampling techniques such as nearest neighbor, bi-linear interpolation, or cubic convolution (see, for instance, Richards (1986)) can be used to estimate the most representative pixel intensity at this location. This intensity is then assigned to the pixel under processing on the corrected image. This process is repeated for every pixel on the virtual corrected image. Upon completion of the spherical distortion correction, the resulting image should be considered as a conventional image and, consequently, can undergo conventional processes.

Image Rectification

Simple image rectification, based on the well known two-dimensional (2D) projective transformation, can be conducted on precorrected fisheye images. According to this technique, a minimum of four control points, falling on a common plane, are needed to estimate the eight-parameter projective transformation. When more than four points are observed, the least-squares method allows one to find the best estimates for the parameters. Obviously, all object parts being out of the rectification plane suffer from a certain amount of deformation. The practical importance of this situation must be evaluated for every application with respect to the required accuracy.

Stereocompilation of Corrected Fisheye Images

Once the spherical distortions are removed from a pair of fisheye images, the perspective views may be analyzed utilizing stereoscopic vision if a proper orientation is carried out. The images being digital, a softcopy photogrammetric system must be involved in the treatment of the stereopair. The only prerequisite for the model orientation concerns the knowledge of the equivalent principal distance of the synthetic images (corrected fisheye images). Because the scale of the corrected image is arbitrarily fixed before the correction process, the principal distance does not represent the hemispherical radius as illustrated in Figure 2. One simple way to estimate this principal distance is to use the collinearity equation in a calibration operation. A certain number of control points must be known as well as some *a priori* information concerning the position and attitude of the camera. Because the image position of the control points is expressed in terms of pixels, the collinearity equation leads to an estimation of the principal distance in the same units (pixels). During the relative orientation, these units are propagated in the model formation, but the absolute orientation transforms the model units (pixels) into more conventional ones (e.g., mm).

Practical Experiments

Three practical tests have been conducted in order to evaluate the performance of the proposed methods. These tests are closely related to the practical problem of mapping underground electric cable access wells. These wells, usually situated at electric distribution network nodes, are very small, that is, typically 1.5 by 3 m. Electricity companies often need to know different information about these wells, notably, the distance between cables and the floor clearance.

The camera used for these tests was a Pentax KX 35-mm equipped with a Sigma 15-mm *f*/2.8 fisheye polar lens. Black-and-white pictures of wells and calibration objects were taken. The film was developed by Kodak™ which also

Table 1. Planimetric Accuracy of a Rectified Image

distance no.	actual (m)	measured (m)	error (m)	distance no.	actual (m)	measured (m)	error (m)
1	1.800	1.785	0.015	8	1.811	1.810	0.001
2	1.800	1.806	−0.006	9	1.166	1.164	0.002
3	1.000	0.996	0.004	10	1.166	1.170	−0.004
4	1.000	0.998	0.002	11	1.789	1.784	0.005
5	2.059	2.057	0.002	12	1.789	1.784	0.005
6	2.059	2.060	−0.001	13	1.789	1.791	−0.002
7	1.811	1.800	0.011	14	1.789	1.792	−0.003
						R.M.S.E.	±0.006

scanned the fisheye photographs at a resolution of 2167 DPI. Among these images, some were used for the calibration of the camera-lens combination. This calibration, carried out under lighting and geometric conditions similar to those encountered in wells, has determined the principal point location and the radius of the hemispherical lens. Surprisingly, the location of the principal point, determined using the lens hood, was off the image center by more than 1 mm. This deviation was mostly in the direction of the film drive. Furthermore, this estimate was quite different if another image taken with the lens hood was considered. Suspecting the metric quality of the Kodak scanning, the same experiment was conducted using the negatives but, this time, scanned in-house at a resolution of 600 DPI. The principal point was then estimated to be located at less than 90 µm from the physical image center, and the variation from one picture to the other was less than the dimension of a pixel. Thus, it is possible that the starting position of each image is not constant over an entire roll of film. However, in Kodak's defense, it must be said that this service is obviously not intended for photogrammetrists. Consequently, all the photographs used for the practical tests were scanned with a conventional scanner at a resolution of 600 DPI. Also, considering the relatively small offset between the principal point and the image center, these two points have been assumed to be identical.

The first test goal was to estimate the planimetric accuracy of a rectified fisheye image of a well wall. A laboratory simulation was used to simplify the creation of a set of check points. It consisted in taking a fisheye photograph of a 1- by 1.8-m grid showing crosses at every 20 cm (Figure 3). The view angle of about 45° from the normal of the grid and the object distance of approximately 1 m from the center of the grid correspond to the usual conditions encountered in an underground cable access well. After the correction of spherical distortions (see Figure 4), the four corner crosses were used to define the rectification plane. The DVR-2™ rectification software was used for the transformation (Boulianne *et al.*, 1992). A set of ten distances covering the entire grid were measured on the rectified view (Figure 5) and later compared with their real values. Table 1 shows the result of the comparison. The ±6-mm RMSE for distances obtained largely satisfies the electricity company needs. Of course, this accuracy could have been improved by scanning the original image at a higher resolution.

In the second test, the rectification approach was applied in a real underground cable access well to verify the visual quality and usefulness of a rectified image. For the test, two 500-watt lamps were taken down into the well. Also, a set of three poles were placed at a distance corresponding to the average cable distance from the wall. The first one, a telescopic rod, was wedged in place horizontally between the opposite walls near the top of the well (Figure 6). The other two were suspended vertically on the first rod. The lengths of the rods and the distance between them were measured and used to define a set of reference coordinates. These coordinates are considered as error free in the present context. Including the time necessary for the establishment of this rectification system, acquisition of the photographs took approximately 15 minutes. Figures 6 and 7 show the original distorted picture and the final rectified image, respectively (for the sake of conciseness, the intermediate corrected image for spherical distortions is not presented in this paper). By inspecting the control rods in Figure 7, one can note that the

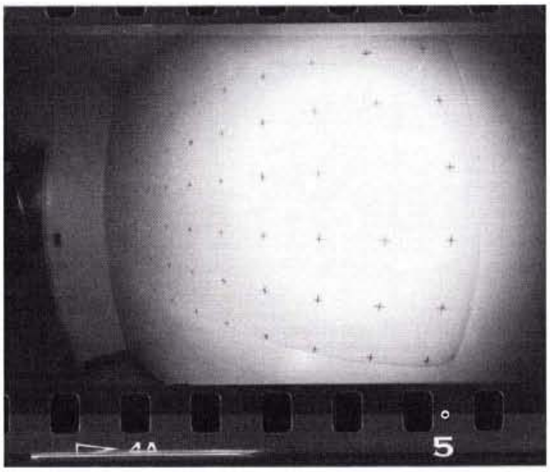

Figure 3. Photograph of a grid with a 15-mm fisheye lens.

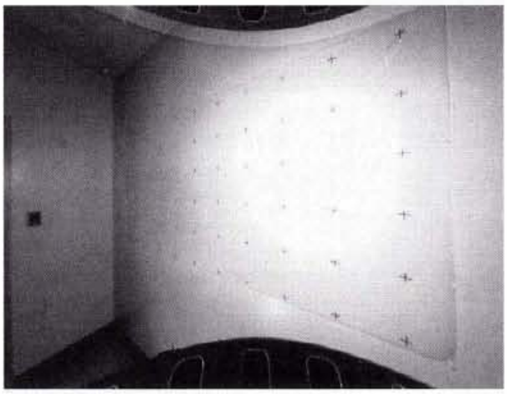

Figure 4. Grid corrected image.

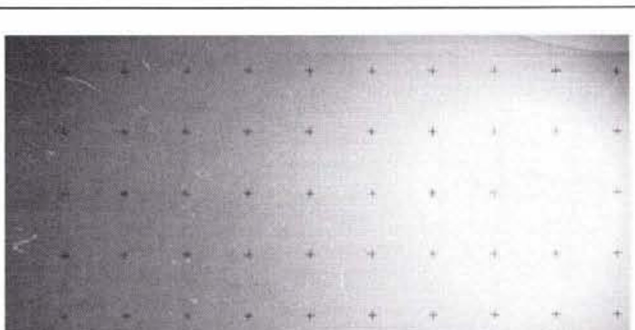

Figure 5. Grid rectified image.

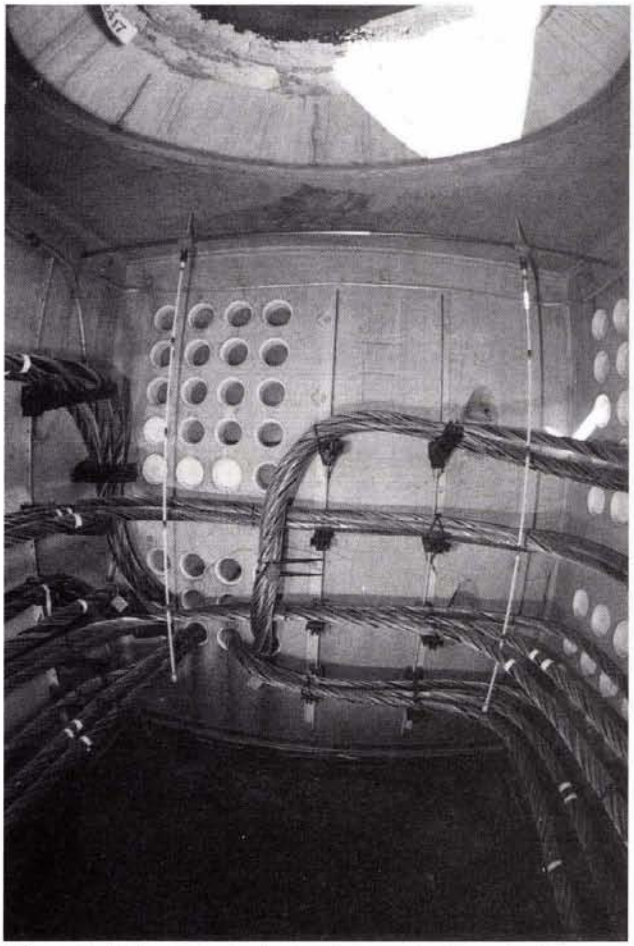

Figure 6. Fisheye photograph of an underground cable access well.

fisheye effect has been properly removed because the rods appear perfectly straight and form a rectangle. The rectified image can be imported into any CAD which accepts raster data for measurement or vectorization. Besides the possibility to extract planimetric information from this image, the image itself offers a very useful view of the entire well wall for the practitioners. For instance, this view provides information about the availability of supply pipes in the walls.

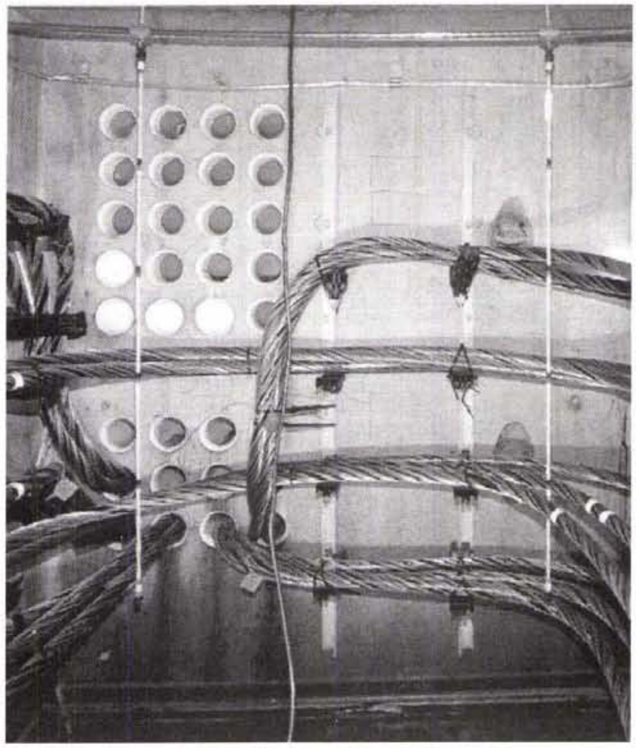

Figure 7. Rectified image of a well wall.

The third experiment consisted of testing the accuracy of spatial data extracted from a model created by two precorrected fisheye images. As for the previous tests, the geometric conditions were selected to reproduce, as closely as possible, the practical mapping operation for a well. A metallic frame composed of five vertical rods with each rod having three control marks was used for this experiment (Figure 8). The frame occupies a volume of approximately 1 m^3. The accuracy of the control was estimated to be ± 0.5 mm which, in this context, is considered again as error free. Among the 15 points, six served for the model absolute orientation (point numbers 1,3,4,6,10,12) while the others were considered as check points (point numbers 2,5,7,8,9,11,13,14,15). Stereo fisheye photographs of the cube were taken from an approximate distance of 70 cm with a stereoscopic base of 40 cm. The corrected images (Figure 9) were afterwards oriented

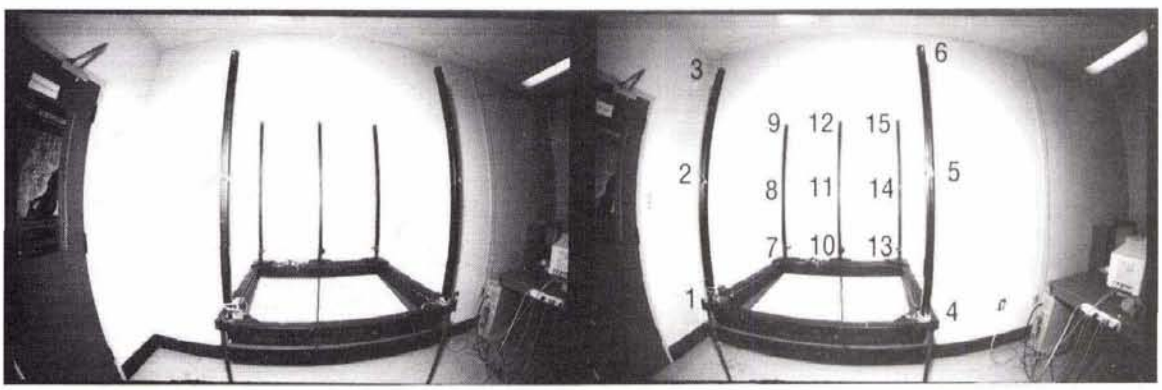

Figure 8. Fisheye stereopair of a test frame.

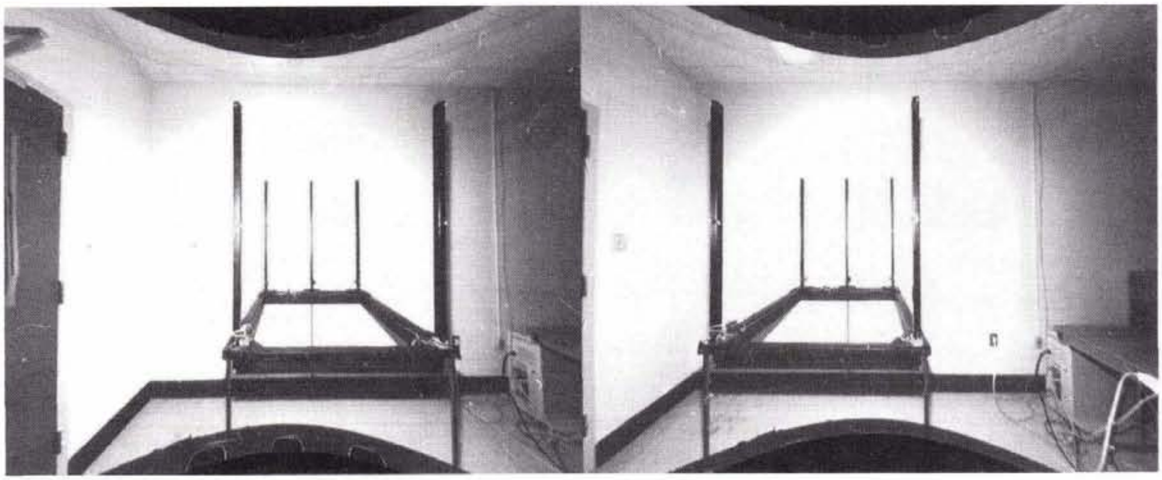

Figure 9. Corrected stereopair of the test frame.

using the digital photogrammetric workstation DVP™ (Gagnon *et al.*, 1990).

Table 2 presents the comparison between photogrammetric coordinates of the check points and the actual coordinates. A global RMSE of ±5.8 mm was obtained $((3^2 + 3^2 + 4^2)^{1/2})$, which is equivalent to the planimetric accuracy estimated by the first test. Considering that the pixel size in the middle of the cube measures approximately 2 mm by 2 mm by 6 mm (1 mm by 1 mm by 2 mm for the front face of the cube and 3 mm by 3 mm by 10 mm at the rear), the spatial accuracy corresponds to approximately 1 pixel. In the context of an electrical distribution system, this accuracy exceeds the requirements.

Conclusions

Two methods, based on the utilization of fisheye photographs, for mapping confined areas have been presented in this paper. Unlike other applications of this kind of image, correction of spherical distortions are applied to fisheye images prior to their utilization as conventional images. For relatively flat objects located in a very restrained areas, the rectification of precorrected fisheye images can be a more efficient alternative than conventional surveys. In a test conducted in an environment similar to an underground access well, a planimetric accuracy of ± 6 mm was achieved. In addition, the rectified image represents a more visual and useful product than a simple map. When the third dimension is required, stereopairs of corrected images can be treated successfully in a softcopy photogrammetric system. A practical test demonstrated that a spatial accuracy of one pixel (~ 6 mm) can be observed. These results are even more acceptable considering that the lens used is ten times less expensive than high-quality fisheye lenses.

For future applications of the proposed methods, one should consider the possibility of using a digital camera with a fisheye lens. This would obviously eliminate the frequent long delays inherent to film development. However, the resolution of today's CCD chips in such cameras would yield a lower accuracy.

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TABLE 2. SPATIAL ACCURACY OF A FISHEYE MODEL

point	actual coordinates (m)			measured coordinates (m)			error (m)		
	X	Y	Z	X	Y	Z	ΔX	ΔY	ΔZ
2	0.786	−0.886	−2.312	0.783	−0.890	−2.316	0.003	0.004	0.004
5	1.584	−0.892	−2.306	1.588	−0.892	−2.316	−0.004	0	0.004
7	0.785	−1.354	−3.183	0.787	−1.352	−3.175	−0.002	−0.002	−0.008
8	0.789	−0.903	−3.177	0.789	−0.903	−3.176	0	0	−0.001
9	0.791	−0.450	−3.181	0.793	−0.453	−3.176	−0.002	0.003	−0.005
11	1.188	−0.903	−3.181	1.190	−0.900	−3.177	−0.002	−0.003	−0.004
13	1.595	−1.354	−3.171	1.596	−1.352	−3.171	−0.001	−0.002	0
14	1.589	−0.901	−3.163	1.593	−0.903	−3.169	−0.004	0.002	0.006
15	1.587	−0.455	−3.165	1.590	−0.452	−3.166	−0.003	−0.003	0.001
						R.M.S.E.	±0.003	±0.003	±0.004

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