

A METHOD AND SYSTEM FOR PROVIDING A SEAMLESS OMNIVIEW IMAGE FROM FISHEYE IMAGES

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FIELD OF THE INVENTION

This invention relates generally to the fields of digital image rendering and image capturing systems, and in particular, to a method and system for providing a normal perspective image with improved resolution at the seams from a set of images captured using a fisheye lens.

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BACKGROUND OF THE INVENTION

Camera viewing systems that use a fisheye lens to capture images and convert the images to normal perspective images are known to those skilled in the art. Generally, these systems capture images using a fisheye lens, typically a which has the advantage of being able to capture the entire 180 degrees of hemispherical field-of-view without having to move the camera. The resulting fisheye image, which, in its original form, is distorted, is then converted to a normal perspective image using a digital image transformation technique.

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One such system is described in the US Patent No. 5,185,667. The principles of this prior art system can be understood by reference to FIG. 1. Shown schematically at 1 is the fisheye lens that provides an image of the environment with a 180 degree field-of-view. The fisheye lens is attached to a camera 2 which converts the optical image into an electrical signal. These signals are then digitized electronically 3 and stored in an image buffer 4

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within the present invention. An image processing system consisting of an X-MAP and a Y-MAP processor shown as 6 and 7, respectively, performs the two-dimensional transform mapping. The image transform processors are controlled by the microcomputer and control interface 5. The
5 microcomputer control interface provides initialization and transform parameter calculation for the system. The control interface also determines the desired transformation coefficients based on orientation angle, magnification, rotation, and light sensitivity input from an input means such as a joystick controller 12 or computer input means 13. The transformed
10 image is filtered by a 2-dimensional convolution filter 8 and the output of the filtered image is stored in an output image buffer 9. The output image buffer 9 is scanned out by display electronics 10 to a video display device 11 for viewing.

A range of lens types can be accommodated to support various fields
15 of view. The lens optics 1 correspond directly with the mathematical coefficients used with the X-MAP and Y-MAP processors 6 and 7 to transform the image. The capability to pan and tilt the output image remains even though a different maximum field of view is provided with a different lens element.

20 This prior art system can be realized by proper combination of a number of optical and electronic devices. The fisheye lens 1 is exemplified by any of a series of wide angle lenses from, for example, Nikon, particularly the 8 mm F2.8. Any video source 2 and image capturing device 3 that converts the optical image into electronic memory can serve as the input for
25 the invention such as a Videk Digital Camera interfaced with Texas Instrument's TMS 34061 integrated circuits. Input and output image buffers

4 and 9 can be constructed using Texas Instrument TMS44C251 video random access memory chips or their equivalents. The control interface can be accomplished with any of a number of microcontrollers including the Intel 80C196. The X-MAP and Y-MAP transform processors 6 and 7 and image
5 filtering 8 can be accomplished with application-specific integrated circuits or other means as will be known to persons skilled in the art. The display driver can also be accomplished with integrated circuits such as the Texas Instruments TMS34061. The output video signal can be of the NTSC RS-170, for example, compatible with most commercial television displays in
10 the United States. Remote control 12 and computer control 13 are accomplished via readily available switches and/or computer systems that also will be well known. These components function as a system to select a portion of the input image (fisheye or wide angle) and then mathematically transform the image to provide the proper perspective for output. The keys
15 to the success of the system include:

(1) the entire input image need not be transformed, only the portion of interest

(2) the required mathematical transform is predictable based on the lens characteristics.

20 The transformation that occurs between the input memory buffer 4 and the output memory buffer 9, as controlled by the two coordinated transformation circuits 6 and 7, is better understood by looking at FIG. 2 and FIG. 3. The image shown in FIG. 2 is a pen and ink rendering of the image of a grid pattern produced by a fisheye lens. This image has a field-of-view
25 of 180 degrees and shows the contents of the environment throughout an entire hemisphere. Notice that the resulting image in FIG. 2 is significantly

distorted relative to human perception. Vertical grid lines in the environment appear in the image plane as 14a, 14b, and 14c. Horizontal grid lines in the environment appear in the image plane as 15a, 15b, and 15c. The image of an object is exemplified by 16. A portion of the image in FIG. 2 has been
5 correct, magnified, and rotated to produce the image shown in FIG. 3. Item 17 shows the corrected representation of the object in the output display. The results shown in the image in FIG. 3 can be produced from any portion of the image of FIG. 2 using the prior art system. Note the perspective corrected as demonstrated by the straightening of the grid pattern displayed
10 in FIG. 3. In the prior art system, these transformations can be performed at real-time video rates (30 times per second), compatible with commercial video standards.

This prior art system has the capability to pan and tilt the output image through the entire field of view of the lens element by changing the
15 input means, e.g. the joystick or computer, to the controller. This allows a large area to be scanned for information as can be useful in security and surveillance applications. The image can also be rotated through 360 degrees on its axis changing the perceived vertical of the displayed image. This capability provides the ability to align the vertical image with the gravity
20 vector to maintain a proper perspective in the image display regardless of the pan or tilt angle of the image. The system also supports modifications in the magnification used to display the output image. This is commensurate with a zoom function that allows a change in the field of view of the output image. This function is extremely useful for inspection operations. The
25 magnitude of zoom provided is a function of the resolution of the input camera, the resolution of the output display, the clarity of the output display,

and the amount of picture element(pixel) averaging that is used in a given display. The system supports all of these functions to provide capabilities associated with traditional mechanical pan (through 180 degrees), tilt (through 180 degrees), rotation (through 360 degrees), and zoom devices.

- 5 The system also supports image intensity scaling that emulates the functionality of a mechanical iris by shifting the intensity of the displayed image based on commands from the user or an external computer.

The postulates and equations that follow are based on this prior art system utilizing a fisheye lens as the optical element. There are two basic
 10 properties and two basic postulates that describe the perfect fisheye lens system. The first property of a fisheye lens is that the lens has a 2π steradian field-of-view and the image it produces is a circle. The second property is that all objects in the field-of-view are in focus, i.e., the perfect fisheye lens has an infinite depth-of-field. The two important postulates of the fisheye lens system
 15 (refer to FIGS. 4 and 5) are stated as follows;

Postulate 1: Azimuth angle invariability—For object points that lie in a content plane that is perpendicular to the image plane and passes through the image plane origin, all such points are mapped as image points onto the line of intersection between the image plane and the content plane, i.e. along a radial
 20 line. The azimuth angle of the image points is therefore invariant to elevation and object distance changes within the content plane.

Postulate 2: Equidistant Projection Rule—The radial distance, r , from the image plane origin along the azimuth angle containing the projection of the object point is linearly proportional to the zenith angle β , where β is defined as
 25 the angle between a perpendicular line through the image plane origin and the line from the image plane origin to the object point. Thus the relationship:

$$r = k\beta \quad (1PA)$$

Using these properties and postulates as the foundation of the fisheye lens system, the mathematical transformation for obtaining a perspective corrected image can be determined. FIG. 4 shows the coordinate reference frames for the object plane and the image plane. The coordinates u, v describe object points within the object plane. The coordinates x, y, z describe points within the image coordinate frame of reference.

The object plane shown in FIG. 4 is a typical region of interest to determine the mapping relationship onto the image plane to properly correct the object. The direction of view vector, $DOV[x, y, z]$, determines the zenith and azimuth angles for mapping the object plane, UV , onto the image plane, XY . The object plane is defined to be perpendicular to the vector, $DOV[x, y, z]$. The formulas for obtaining the transformation to obtain a perspective corrected image are the following:

$$x = \frac{R[uA - vB + mR\sin\beta\sin\partial]}{\sqrt{u^2 + v^2 + m^2 R^2}} \quad (2PA)$$

$$y = \frac{R[uC - vD + mR\sin\beta\cos\partial]}{\sqrt{u^2 + v^2 + m^2 R^2}} \quad (3PA)$$

where:

$$A = (\cos \varnothing \cos \partial - \sin \varnothing \sin \partial \cos \beta)$$

$$B = (\sin \varnothing \cos \partial + \cos \varnothing \sin \partial \cos \beta)$$

$$C = (\cos \varnothing \sin \partial + \sin \varnothing \cos \partial \cos \beta)$$

$$D = (\sin \varnothing \sin \partial - \cos \varnothing \cos \partial \cos \beta)$$

and where:

- 5 R = radius of the image circle
- β = zenith angle
- ∂ = Azimuth angle in image plane
- $\varnothing$ = Object plane rotation angle
- m = Magnification
- 10 u, v = object plane coordinates
- x, y = image plane coordinates.

The equations 2PA and 3PA provide a direct mapping from the UV space to the XY image space and are the fundamental mathematical result

15 that supports the functioning of the prior art system. By the knowing the desired zenith, azimuth, and object plane rotation angles and the magnification, the locations of x and y in the imaging array can be determined. This approach provides a means to transform an image from the input video buffer to the output video buffer exactly. Also, the system is

20 completely symmetrical about the zenith, therefore, the vector assignments and resulting signs of various components can be chosen differently depending on the desired orientation of the object plane with respect to the image plane.

This system has many uses. For instance, it can be used as a surveillance system, U.S. Pat. No. 5,359,363, or an endoscopy system, U.S. Pat. No. 5,313,306. For some of the uses, it is useful to have a full 360 degree field-of-view. To produce a perspective corrected image with a full
5 360 degree field-of-view, two fisheye lens are used to capture two 180-degree images. These fisheye images are then converted to normal perspective images and then combined to form a single perspective image containing the full 360 degree field-of-view.

Some shortcomings exist for this prior system when using it to view
10 the 360 degree field-of-view image. Due to the structure of the fisheye lens, a fisheye image has lower resolution near the edge. Therefore, when the images are combined, there will be some degradation of image quality at the seam where the two images are combined. Although these poor-quality areas can be enhanced to some degree through the use of various
15 image processing techniques, the final image will not be truly "seamless". Moreover, with this prior art system, it is difficult to equalize the light intensity for each of the images, and hence, sometimes producing a perspective image with uneven lighting. In addition, it takes a relatively large amount of memory to store the fisheye images. This can be
20 particularly problematic when large number of images are stored in a storage medium, or when the image files need to be transmitted over a network.

OBJECTS OF THE INVENTION

Therefore, it is an object of the present invention to provide a method for producing perspective image which is substantially seamless.

It is another object of the present invention to provide a method for producing perspective image which always has even lighting.

5 It is another object of the present invention to provide an image file which uses less memory storage space.

SUMMARY OF THE INVENTION

10 Applying the same two basic properties and the two basic postulates discussed in the Background portion, the present invention employs a two-step transformation where the fisheye image is first mathematically transformed into an intermediate angular image, and the angular image is then transformed into a perspective corrected image.

15 To obtain a perspective corrected image having a 360 degree field-of-view, the present system begins by first obtaining a set of three fisheye images separated by 120 degrees. This can be accomplished simply by taking a first picture with a camera using the fisheye lens, rotating the camera view by 120 degrees and taking another picture, rotating the view
20 again by 120 degrees and taking the third and the last picture. Hence, each of the three fisheye images has a 60 degree image overlap with its neighboring fisheye image.

 After the three fisheye images in the digitized form are obtained, the images are transformed into angular images using a mathematical
25 transformation. The resulting three angular images are then combined to form a single angular image having 360 degree field-of-view. Because the

fish-eye images were taken 120 degrees apart using a fish-eye lens having a steradian of 180 degrees, there is 60 degrees of overlap between the adjacent images.

The precise boundaries of the overlap are determined basically by
5 comparing the pixels of the overlapping images and looking for a match. The image in the 60 degree overlap of one angular image should be similar to that of the image of its corresponding overlapping angular image, but they are not identical due to variations in the resolution. Therefore, the boundaries are determined by finding the degree of overlap which
10 produces the minimum difference in pixel intensity value between the two overlapping angular images.

Once the final angular image is formed, the light intensities of the duplicative pixels in the overlapping area are adjusted. Because the resolution of the angular image is better near the center than the edges,
15 the intensity of the pixels which are nearer to the center is increased while the intensity of the pixels which are nearer to the edge is lowered. In the preferred embodiment, for each angular image, 30 degrees of the overlap area which is nearest to the center is given 90 percent intensity, while the other 30 degrees of the overlap area which is farthest from the center (and
20 nearest to the edge) is given 10 percent intensity. Once the proper intensity levels have been applied to the sections of the overlap area, much of the picture degradation attributed to the edges can be eliminated to produce a seamless look.

Once the final angular image has been attained, the combined
25 angular image is finally transformed into the perspective corrected image. This is done basically by converting the points in the combined angular

image, and applying a transformation matrix to perform tilt, pan and roll to obtain the points in the perspective image.

The present transformation method of first converting the fisheye image to the angular image, and then converting the angular image to the perspective corrected image offers a number of advantages over the prior art. For one, the angular images, due their mathematical properties, can be easily combined unlike the fisheye images. Depending on how much overlap there is, much of the resolution degradation can be eliminated. Moreover, the overlap area provides a reference point to compare light intensities of the respective images, and hence, allows a convenient way to normalize the lighting for the final perspective corrected image. Furthermore, the angular image generally takes up less memory space than the fisheye image of comparable field-of-view.

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BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 (prior art) shows a schematic block diagram of the prior art system illustrating the major components thereof.

FIG. 2 (prior art) is an example sketch of a typical fisheye image used as input by the prior art system.

FIG. 3 (prior art) is an example sketch of the output image after correction for a desired image orientation and magnification within the original image.

FIG. 4 (prior art) is a schematic diagram of the fundamental geometry that the prior art system embodies to accomplish the image transformation.

FIG. 5 (prior art) is a schematic diagram demonstrating the projection of the object plane and position vector into image plane coordinates.

FIG. 6 is a mathematical representation of the fundamental geometry
5 that the present invention embodies to accomplish the image transformation from the fisheye image to angular image.

FIG. 7 is a mathematical representation of the angular image plotted on a (θ, ϕ) coordinate system.

FIG. 8 is a schematic diagram illustrating how the three angular
10 images are combined.

FIG. 9 is a mathematical representation of the combined angular image plotted on a (θ, ϕ) coordinate system.

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DETAILED DESCRIPTION OF THE INVENTION

The present invention employs the same system hardware as was used in the prior art system described in the Background section. However, by employing a unique mathematical transformation algorithm,
20 the present invention is able to overcome the shortcomings mentioned above. For convenience in describing the present invention, it shall be assumed that the hardware described above is used, though other similar set of hardware can be employed as well.

Although the present description of the invention is sufficient for one
25 of ordinary skilled in the art to make and use the invention, it is useful to obtain the following publication which provides some of the theoretical

mathematical foundation for the transformation method: McMillan, Leonard and G. Bishop, *"Plenoptic Modeling: An Image-Based Rendering System,"* Proceedings of SIGGRAPH 95, Los Angeles, California, August 6-11, 1995.

5 In the prior art system described in the Background portion, the system mapped directly from the XY space (fisheye image) to the UV space (perspective image) for facilitating the mathematical transformation for obtaining a perspective corrected image. However, the present invention employs a two-step transformation where the fisheye image is
10 first mathematically transformed into an intermediate angular image, and the angular image is then transformed into a perspective corrected image. It should be appreciated by one skilled in the art, however, that while the transformation techniques differ, the two basic properties and the two basic postulates discussed in the Background portion still applies to the present
15 invention.

 In describing the present invention, the term "fisheye image" shall be used to refer to the digitized form of the image directly obtained by taking a picture using the fisheye lens. The term "angular image" shall be used to denote an intermediate image obtained by mathematical transforming the
20 digitized fisheye image. It should be understood, however, that the angular image is not really an "image" in the sense that it is not used for viewing; it is simply a mathematical conversion which gives the present invention its flexibility. Lastly, the term "perspective corrected image" shall refer to the final image which is used for viewing.

25 To obtain a perspective corrected image having a 360 degree field-of-view, the present system begins by first obtaining a set of three fisheye

images separated by 120 degrees. This can be accomplished simply by taking a first picture with a camera using the fisheye lens, rotating the camera view by 120 degrees and taking another picture, rotating the view again by 120 degrees and taking the third and the last picture. The fisheye lens preferably has steradian 180 degree, though it is possible to use
 5 fisheye lens having less than 180 degree field-of-view (in which case more pictures need to be taken or the degree of overlap will be different). Hence, each of the three fisheye images has a 60 degree image overlap with its neighboring fisheye image. The purpose and the usefulness of this
 10 overlap in image will be discussed further down below.

After the three fisheye images in the digitized form are obtained, the images are transformed into angular images. FIG. 6 shows a mathematical representation of a fisheye image with a point on the fisheye image being represented by (x,y) and its direction vector represented by P[dx,dy,dz].
 15 FIG. 7 illustrates the angular image with a point on the image being represented by (θ, ϕ) . The following equations are used for converting the fisheye image into the angular image in P[dx,dy,dz] coordinates.

$$x = (dx)(w) \quad (1)$$

$$20 \quad y = (dy)(w) \quad (2)$$

where

$$w = \frac{\tan^{-1} \left(\frac{\sqrt{dx^2 + dy^2}}{dz} \right)}{\frac{\pi}{2} \left(\sqrt{dx^2 + dy^2} \right)}$$

and

$$dx = \sin \theta$$

$$dy = (\tan \phi) \left(\sqrt{dx^2 + dy^2} \right)$$

$$dz = \cos \theta$$

5

Using equations 1 and 2, each of the three fisheye images are converted to the angular image. As can be seen from FIG. 7, the angular image is plotted on a (θ, ϕ) coordinate system making it easy to combine the images.

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The resulting three angular images are combined as illustrated in FIG. 8. Because the fisheye images were taken 120 degrees apart using a fisheye lens having a steradian of 180 degrees, there is 60 degrees of overlap between the adjacent images. Hence, as can be seen from FIG. 8, the angular image 1 overlaps angular image 2 by about 60 degrees, and the angular image 2 overlaps angular image 3 also by about 60 degrees.

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The precise boundaries of the overlap are determined basically by comparing the pixels of the overlapping images and looking for a match. The image in the 60 degree overlap of one angular image should be similar to that of the image of its corresponding overlapping angular image, but they are not identical due to variations in the resolution. Therefore, the boundaries are determined by finding the degree of overlap which produces the minimum difference in pixel intensity value between the two overlapping angular images using the following equation:

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$$e = \sum_i \left[I_1(\theta, \phi) - I_2(\theta + m_\theta, \phi) \right]^2 \quad (3)$$

where,

I = Intensity of the pixel

e = root mean square

5 m_θ = degree of overlap

Using equation 3, the degree of overlap which produces the minimum e value is chosen. Since it is known in the beginning approximately how much overlap there will be, in this case 60 degrees, it is more efficient to try
 10 out only those values near 60 degrees, e.g., between 40 degrees and 70 degrees, and not all values need to be tested. Once the boundaries are determined, the images are combined.

The final angular image after the three angular images are combined is shown in FIG. 9. As can be seen from FIG. 9, the combined
 15 angular image has the full 360 degree of field-of-view. Once the final angular image is formed, the light intensities of the duplicative pixels in the overlapping area are adjusted. Because the resolution of the angular image is better near the center (at 0 degrees, FIG. 7) than the edges (at 90 and -90 degrees, FIG. 7), the intensity of the pixels which are nearer to the
 20 center is increased while the intensity of the pixels which are nearer to the edge is lowered. In the preferred embodiment, for each angular image, 30 degrees of the overlap area which is nearest to the center is given 90 percent intensity, while the other 30 degrees of the overlap area which is farthest from the center (and nearest to the edge) is given 10 percent
 25 intensity. These values provided, however, may be adjusted to some extent

without unduly affecting the quality of the final perspective corrected image. Once the proper intensity levels have been applied to the sections of the overlap area, much of the picture degradation attributed to the edges can be eliminated to produce a seamless look.

- 5 Once the final angular image has been attained as shown in FIG. 9, the combined angular image is finally transformed into the perspective corrected image. This is done basically by converting the points in the combined angular image, represented by (θ, ϕ) , into a vector, $[dx, dy, dz]$, and applying a transformation matrix to perform tilt, pan and roll to obtain
- 10 the points in the perspective image which are represented by (u,v) . The equations below are used for the conversion:

$$\theta = \tan^{-1} \left(\frac{dx}{dz} \right) \quad (4)$$

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$$\phi = \tan^{-1} \left(\frac{dy}{\sqrt{dx^2 + dz^2}} \right) \quad (5)$$

The transform matrix of the vectors $[dx, dy, dz]$ are shown as below:

$$\begin{aligned} dx &= (a_x u') + (b_x v') + c_x \\ dy &= (a_y u') + (b_y v') + c_y \quad \text{where } u' = (u)(f), v' = (v)(f) \\ dz &= (a_z u') + (b_z v') + c_z \end{aligned}$$

where,

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \left(R_x(-\beta) R_y(\alpha) R_z(\Omega) \right) \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \quad \text{where } R=\text{rotation}$$

to yield,

$$a_x = \cos(\Omega) \cos(\alpha)$$

$$a_y = \sin(\Omega) \cos(\alpha) + \cos(\Omega) \sin(\alpha) \sin(\beta)$$

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$$a_z = \sin(\Omega) \sin(\beta) - \cos(\Omega) \sin(\alpha) \cos(\beta)$$

and

$$\begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix} = \left(R_x(-\beta) R_y(\alpha) R_z(\Omega) \right) \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$

to yield,

$$b_x = -\sin(\Omega) \cos(\alpha)$$

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$$b_y = \cos(\Omega) \cos(\beta) - \sin(\Omega) \sin(\alpha) \sin(\beta)$$

$$b_z = \cos(\Omega) \sin(\beta) + \sin(\Omega) \sin(\alpha) \cos(\beta)$$

and

$$\begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix} = \left(R_x(-\beta) R_y(\theta) R_z(\Omega) \right) \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

to yield,

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$$c_x = \sin(\alpha)$$

$$c_y = -\cos(\alpha) \sin(\beta)$$

$$c_z = \cos(\alpha) \cos(\beta)$$

and where,

Ω = roll angle

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α = pan angle

β = pitch angle

f = focal length.

The equations 4 and 5 provide a means for mapping from the angular
5 image of FIG. 9 to the perspective corrected image. The perspective
corrected image can be further enhanced through the various known image
processing techniques.

The present transformation method of first converting the fisheye
image to the angular image, and then converting the angular image to the
10 perspective corrected image offers a number of advantages over the prior
art. For one, the angular images, due their mathematical properties, can be
easily combined unlike the fisheye images. Depending on how much
overlap there is, much of the resolution degradation can be eliminated.
Moreover, the overlap area provides a reference point to compare light
15 intensities of the respective images, and hence, allows a convenient way to
normalize the lighting for the final perspective corrected image.
Furthermore, the angular image generally takes up less memory space than
the fisheye image of comparable field-of-view.

The present invention may be embodied in other specific forms
20 without departing from the spirit or essential characteristics thereof. For
instance, although here the preferred embodiment of the transformation
method was described in relation to an image having 360 degree field-of-
view, it is possible to use the present method on an image having less than
360 degree field-of-view by using a fisheye lens having a steradian of less
25 than 180 degrees. In addition, although it is preferred that three angular

images are used, it is possible to combine only two angular images if less than 360 degree field-of-view is desired for the final perspective image.

The presently disclosed embodiments are, therefore, to be considered in all respects as illustrative and not restrictive, the scope of the invention being indicated by the appended claims and all changes which
5 come within the meaning and range of equivalency of the claims are, therefore, to be embraced therein.

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$$w = \frac{\tan^{-1} \left(\frac{\sqrt{dx^2 + dy^2}}{dz} \right)}{\frac{\pi}{2} \left(\sqrt{dx^2 + dy^2} \right)}$$

8

and

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$$dx = \sin \theta$$

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$$dy = (\tan \phi) \left(\sqrt{dx^2 + dy^2} \right)$$

11

$$dz = \cos \theta$$

12

where

13

x, y = points on fisheye image

14

θ, ϕ = points on angular image

15

dx, dy, dz = direction vector coordinates

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3. The method as claimed in Claim 2 wherein the final combined
2 angular image is transformed into the perspective corrected image using
3 the following equations:

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$$\theta = \tan^{-1} \left(\frac{dx}{dz} \right)$$

5

$$\phi = \tan^{-1} \left(\frac{dy}{\sqrt{dx^2 + dz^2}} \right)$$

6

where

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$$dx = (a_x u') + (b_x v') + c_x$$

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$$dy = (a_y u') + (b_y v') + c_y$$

where $u' = (u)(f)$, $v' = (v)(f)$

9

$$dz = (a_z u') + (b_z v') + c_z$$

10

and where

11

$$a_x = \cos(\Omega) \cos(\alpha)$$



$$a_y = \sin(\Omega) \cos(\alpha) + \cos(\Omega) \sin(\alpha) \sin(\beta)$$

$$a_z = \sin(\Omega) \sin(\beta) - \cos(\Omega) \sin(\alpha) \cos(\beta)$$

$$b_x = -\sin(\Omega) \cos(\alpha)$$

$$b_y = \cos(\Omega) \cos(\beta) - \sin(\Omega) \sin(\alpha) \sin(\beta)$$

$$b_z = \cos(\Omega) \sin(\beta) + \sin(\Omega) \sin(\alpha) \cos(\beta)$$

$$c_x = \sin(\alpha)$$

$$c_y = -\cos(\alpha) \sin(\beta)$$

$$c_z = \cos(\alpha) \cos(\beta)$$

and where,

Ω = roll angle

α = pan angle

β = pitch angle

f = focal length

u, v = points on perspective corrected image

4. The method as recited in Claim 3 wherein boundaries of where first and second angular images overlap are determined by finding a degree of overlap which minimizes e where,

$$e = \sum_i [I_1(\theta, \phi) - I_2(\theta + m_\theta, \phi)]^2$$

and where,

I = Intensity of the pixel

e = root mean square

m_θ = degree of overlap



1 5. The method as recited in Claim 4 wherein intensity of duplicative
2 pixels nearer to a center of an angular image is higher than intensity of
3 duplicative pixels nearer to an edge of an angular image.

1 6 A method for providing a seamless perspective corrected image
2 having 360 degree field-of-view comprising:

3 obtaining a first fisheye image, a second fisheye image, and a third
4 fisheye image, wherein at least a portion of said first fisheye image
5 overlaps said second fisheye image, and at least a portion of said second
6 fisheye image overlaps said third fisheye image, and ;

7 transforming a first fisheye image to form a first angular image;

8 transforming a second fisheye image to form a second angular
9 image;

10 transforming a third fisheye image to form a third angular image;

11 combining said first, second, and third angular images to form a final
12 combined angular image, said first angular image overlapping said
13 second angular image, said second angular image overlapping said
14 third angular, and said final combined angular image having a 360
15 degree field of view;

16 adjusting relative intensities of duplicative pixels in said combined
17 angular image; and

18 transforming said final angular image to form the perspective
19 corrected image.

1 7. The method as claimed in Claim 6 wherein said first, second, and
2 third fisheye images are transformed into said first, second, and third
3 angular images using the following equations:



$$x = (dx)(w)$$

$$y = (dy)(w)$$

where

$$w = \frac{\tan^{-1} \left(\frac{\sqrt{dx^2 + dy^2}}{dz} \right)}{\frac{\pi}{2} \left(\sqrt{dx^2 + dy^2} \right)}$$

and

$$dx = \sin \theta$$

$$dy = (\tan \phi) \left(\sqrt{dx^2 + dy^2} \right)$$

$$dz = \cos \theta$$

where

x, y = points on fisheye image

θ, ϕ = points on angular image

dx, dy, dz = direction vector coordinates

8. The method as claimed in Claim 7 wherein the final combined angular image is transformed into the perspective corrected image using the following equations:

$$\theta = \tan^{-1} \left(\frac{dx}{dz} \right)$$

$$\phi = \tan^{-1} \left(\frac{dy}{\sqrt{dx^2 + dz^2}} \right)$$

where

$$dx = (a_x u') + (b_x v') + c_x$$

$$dy = (a_y u') + (b_y v') + c_y \quad \text{where } u' = (u)(f), \quad v' = (v)(f)$$



$$dz = (a_z u') + (b_z v') + c_z$$

and where

$$a_x = \cos(\Omega) \cos(\alpha)$$

$$a_y = \sin(\Omega) \cos(\alpha) + \cos(\Omega) \sin(\alpha) \sin(\beta)$$

$$a_z = \sin(\Omega) \sin(\beta) - \cos(\Omega) \sin(\alpha) \cos(\beta)$$

$$b_x = -\sin(\Omega) \cos(\alpha)$$

$$b_y = \cos(\Omega) \cos(\beta) - \sin(\Omega) \sin(\alpha) \sin(\beta)$$

$$b_z = \cos(\Omega) \sin(\beta) + \sin(\Omega) \sin(\alpha) \cos(\beta)$$

$$c_x = \sin(\alpha)$$

$$c_y = -\cos(\alpha) \sin(\beta)$$

$$c_z = \cos(\alpha) \cos(\beta)$$

and where,

Ω = roll angle

α = pan angle

β = pitch angle

f = focal length

u, v = points on perspective corrected image

9. The method as recited in Claim 8 wherein boundaries of where first and second angular images overlap are determined by finding a degree of overlap which minimizes e where,

$$e = \sum_i [I_1(\theta, \phi) - I_2(\theta + m_{\theta}, \phi)]^2$$

and where,

I = Intensity of the pixel

e = root mean square



8 m_θ = degree of overlap

1 10. The method as recited in Claim 9 wherein intensity of duplicative
2 pixels nearer to a center of an angular image is higher than intensity of
3 duplicative pixels nearer to an edge of an angular image.

1 11. A system for providing a seamless perspective corrected image
2 comprising:

3 a camera imaging device for receiving optical images and for
4 producing output signals corresponding to said optical images;

5 fisheye lens means attached to said camera imaging system for
6 producing a plurality of overlapping fisheye images for optical conveyance
7 to said camera imaging system;

8 image capture means for receiving said output signals from said
9 camera imaging system and for digitizing said output signals from said
10 camera imaging system;

11 input image memory means for receiving said digitized signals;

12 image transform processor means for transforming a first fisheye
13 image to form a first angular image; transforming a second fisheye image to
14 form a second angular image; combining said first and second angular
15 image to form a final combined angular image, said first angular image
16 overlapping said second angular image; adjusting relative intensities of
17 duplicative pixels in said combined angular image; and transforming said
18 final angular image to form the perspective corrected image; and

19 output image memory means for receiving said output signals from
20 said image transform processor means and storing said signals in said
21 memory means.



12. The method as claimed in Claim 11 wherein said first and second
fisheye images are transformed into said first and second angular images
using the following equations:

$$x = (dx)(w)$$

$$y = (dy)(w)$$

where

$$w = \frac{\tan^{-1} \left(\frac{\sqrt{dx^2 + dy^2}}{dz} \right)}{\frac{\pi}{2} \left(\sqrt{dx^2 + dy^2} \right)}$$

and

$$dx = \sin \theta$$

$$dy = (\tan \phi) \left(\sqrt{dx^2 + dz^2} \right)$$

$$dz = \cos \theta$$

where

x, y = points on fisheye image

θ, ϕ = points on angular image

dx, dy, dz = direction vector coordinates

13. The method as claimed in Claim 12 wherein the final combined
angular image is transformed into the perspective corrected image using
the following equations:

$$\theta = \tan^{-1} \left(\frac{dx}{dz} \right)$$

$$\phi = \tan^{-1} \left(\frac{dy}{\sqrt{dx^2 + dz^2}} \right)$$

where



$$dx = (a_x u') + (b_x v') + c_x$$

$$dy = (a_y u') + (b_y v') + c_y \quad \text{where } u' = (u)(f), v' = (v)(f)$$

$$dz = (a_z u') + (b_z v') + c_z$$

and where

$$a_x = \cos(\Omega) \cos(\alpha)$$

$$a_y = \sin(\Omega) \cos(\alpha) + \cos(\Omega) \sin(\alpha) \sin(\beta)$$

$$a_z = \sin(\Omega) \sin(\beta) - \cos(\Omega) \sin(\alpha) \cos(\beta)$$

$$b_x = -\sin(\Omega) \cos(\alpha)$$

$$b_y = \cos(\Omega) \cos(\beta) - \sin(\Omega) \sin(\alpha) \sin(\beta)$$

$$b_z = \cos(\Omega) \sin(\beta) + \sin(\Omega) \sin(\alpha) \cos(\beta)$$

$$c_x = \sin(\alpha)$$

$$c_y = -\cos(\alpha) \sin(\beta)$$

$$c_z = \cos(\alpha) \cos(\beta)$$

and where,

Ω = roll angle

α = pan angle

β = pitch angle

f = focal length

u, v = points on perspective corrected image

14. The method as recited in Claim 13 wherein boundaries of where first and second angular images overlap are determined by finding a degree of overlap which minimizes e where,

$$e = \sum_i [I_1(\theta, \phi) - I_2(\theta + m_\theta, \phi)]^2$$

and where,



6 I = Intensity of the pixel

7 e = root mean square

8 m_θ = degree of overlap

1 15. The method as recited in Claim 14 wherein intensity of duplicative
2 pixels nearer to a center of an angular image is higher than intensity of
3 duplicative pixels nearer to an edge of an angular image.