Conclusion

1. The operational principle of TV optical stereo range finder has been described for simultaneous determination of coordinates for a set of objects including moving ones. It is possible to construct the system capable of making the picture of object moving in the territory and to solve the problem of three-dimensional relief reconstruction of the surface.
2. The method of object coordinates calculation being in the stereo zone realised on the system breadboard has been suggested.
3. The technique of error calculation in object coordinate determination in the specified point has been suggested. The results of applying the method of error determination in object coordinates are supported by full-scale tests of the system breadboard.

REFERENCES

1. Shulman M.Ya. Automatic focusing of optical system. – Leningrad: Machinostroyeniye, 1990. – 224 p.
2. Forsite P. Computer vision. Modern approach. – Moscow: «Williams» publishing house, 2004. – 928 p.
3. Methods of image computer processing / Ed. by V.A. Soyfer. – Moscow: Fizmatlit, 2003. – 784 p.

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RECONSTRUCTION ALGORITHM OF SPERICAL IMAGE OBTAINED AT OPERATING WIDE-ANGLE OPTICS

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Reconstruction problem of spherical image obtained at operation of wide-angle optics is considered. Rapid algorithm of pixel-by-pixel reconstruction is suggested. The relations connecting pixels of spherical and reconstructed images have been obtained. The results of the algorithm operation are presented.

Introduction

When using optical cameras, for example, TV ones the parameters of applied optical system are known to be important characteristics [1]. Among the existing standard optical lenses the ultra-wide angle lenses or with so-called fisheye lenses are of particular interest. As a rule, lenses of this type have an observation angle (opening angle) 120...180°. Images produced by such lenses look similar to those of mirror ball or sphere reflection. The example of such an image is shown in Fig. 1.

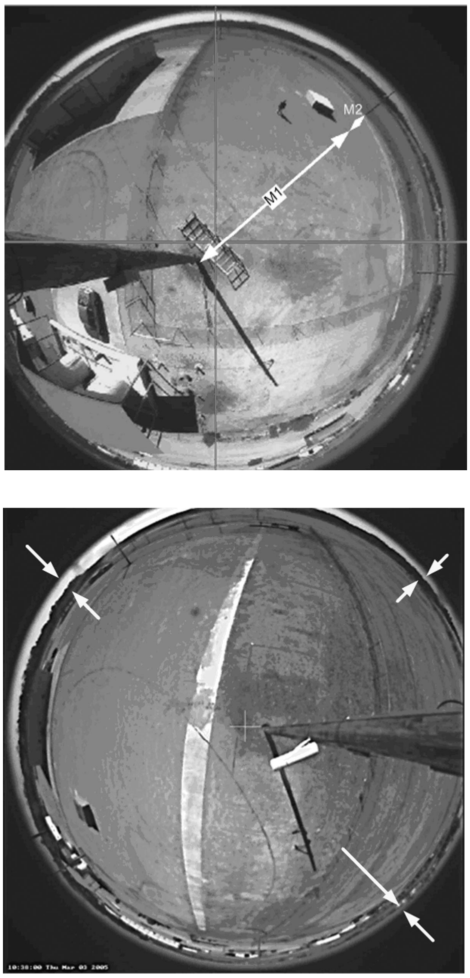
It is seen from the Figure that when directing ultra-wide angle lenses camera vertically to the earth («from the top down») it is possible to «hold» circularly all surrounding territory 360° along the skyline. In this case the skyline is along the whole external part of the circle in the picture. Below in the paper such images are called «spherical».

Spherical images produced by ultra-wide angle lenses can be used in the problems connected with the requirements for wide-angle observation, for example, monitoring of different earth or technical surfaces, video surveillance system, automatic follow-up and navigation system etc. However, there are some difficulties in using spherical images owing to the fact that spherical images contain significant geometric distortions of the information obtained. When operating at spherical images it becomes difficult to estimate all received information and compare it with real objects. Therefore, video systems with conventional lenses are often used. They are fitted with extra position control system which is less efficient and expensive. Hence, there appears the problem of spherical image reconstruction (transformation) to the view suitable for subsequent processing.

Fig. 1. *Example of image produced by ultra-wide angle lenses*

Analysis of spherical images

In Fig. 2 the examples clearly demonstrating the distortions in spherical images are shown. For example, the segments *M*1 and *M*2 presented in the Figure show the same distance on the territory (Fig. 2, *a*).



a

b

Fig. 2. *Examples demonstrating the distortions in spherical images*

Each pixel of spherical image contains the more information on the surface observed, the farther it is from the image centre. Thus, information on the observed surface at the sphere edge is strongly reduced and practically unsuitable for data analysis (Fig. 2, *b*). In other words, distortions in spherical image close to the centre are minimal, but those close to the edge of the circle are maximum.

Following from the mentioned above, one can define four zones in spherical image ranked according to the degree of increase in distortions for an observer – a man. These are A', B', C' and D' zones (Fig. 3). Where A' is the zone of minimal distortions, B' is the zone of average distortions, C' is the zone of strong distortions and D' is the zone of distortions irreversible for reconstruction. It should be noted that when using conventional lenses (i. e. not ultra-wide angle ones) the result of observation is the fragment of image in the zone A'. In this case the distortions typical for spherical images are not present in the image, but the image itself is more detailed, since the same set of pixels of accepted image contains information on significantly less part of the surface observed. Consequently, for video systems with ultra-wide angle lenses the essential advantage is the processing video information contained in the zones B' and C', otherwise, application of ultra-wide angle lenses in most cases would be unpractical.

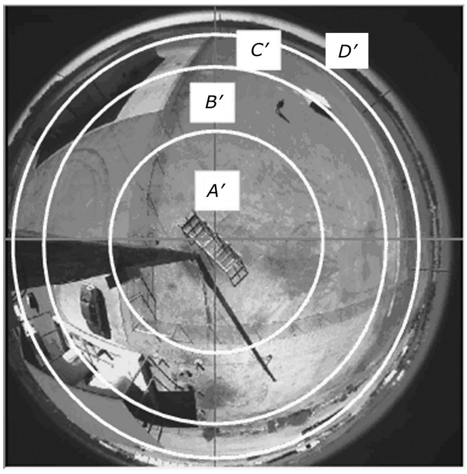


Fig. 3. *Division of spherical image into parts according to the distortion degree*

Reconstruction algorithm

One can show the problem of reconstruction in spherical image clearly by the example of periodic picture on flat surface of, for example, a grid consisting of squares (Fig. 4).

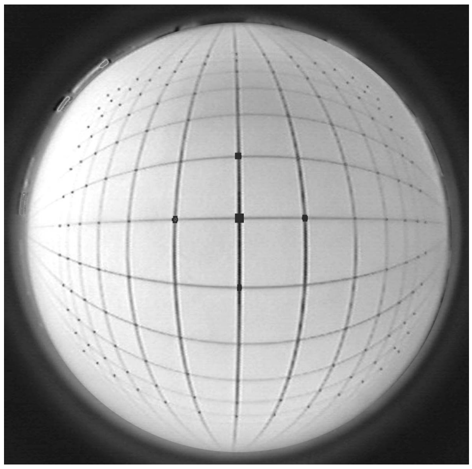


Fig. 4. *Example of spherical image of grid*

In Fig. 4 it is clearly seen that at the edge of spherical image circle (or in the zone D') the boundaries of squares and their content merges in common pixels, whereas in the centre of circle similar information is presented in more details. In Fig. 5 the model of spherical image and the image of ideal (desired) reconstruction is presented in the boundaries of the zones A', B' and C'. The given Figure shows that the lines crossing the centre of circle in the spherical image (central lines) lying in the plane perpendicular to the optical axis stay straight, that is do not curve. If one turns the camera at arbitrary angle around optical axis, the pattern of the grid will turn at the same angle, but will not change. We obtain that any segments belonging to the lines crossing the centre of spherical image are not distorted. Besides, one should conclude that at coincidence of coordinate systems in the spherical image and in the observed plane the angle of slope for arbitrary line crossing the centre of spherical image is equal to the real slope angle of the given line.

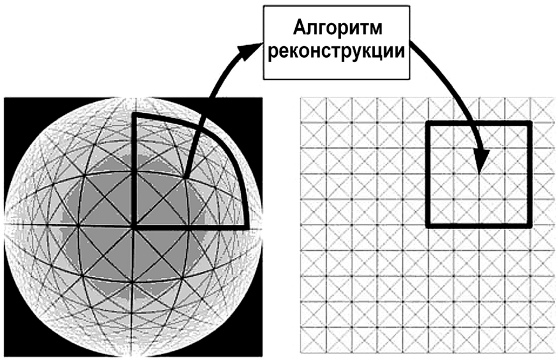


Fig. 5. *Example showing the problem of reconstruction of spherical image*

Let us consider the arbitrary point M' lying in the spherical picture and the point M corresponding to it in the existing ideal-reconstructed image (Fig. 6).

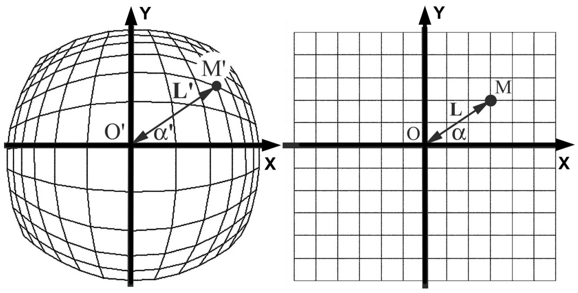


Fig. 6. *Example of one point reconstruction in spherical image*

Since the segments OM and $O'M'$ belong to the straight lines crossing the centre of image, then, from the above reasoning the angles α and α' are equal. If the lengths of the segments L and L' are known, the coordinates of the points M and M' become known. The relation of the segment lengths L to L' is constant for any image equidistant from the centre of point and depends only on characteristics of particular lens, i. e. is a known and calculated parameter.

In the problem on reconstruction of spherical image the coordinates of sought-for point M are known, since these are the coordinates of current image point, the brightness values of which are calculated (reconstructed). Consequently, the angle α and the length L are calculated parameters. Knowing the value of angle α' which is equal to the value of angle α, and knowing the relation of the segment lengths L and L' one can find the coordinates of the sought-for point M'. Thus, the problem on reconstruction of spherical image can be reduced to searching for coordinates of the points in the spherical picture which corresponds to the coordinates of the points in reconstructed image. As applied to digital images it is more convenient to search for the correspondence pixel-by-pixel.

Write down the relationships connecting the coordinates of matrix pixels of reconstructed and spherical image, in the following way:

$$L(x, y) = \sqrt{(x - X_0)^2 + (y - Y_0)^2}, \tag{1}$$

$$\alpha'(x, y) = \alpha(x, y) = \operatorname{arctg}\left(\frac{y - Y_0}{x - X_0}\right), \tag{2}$$

$$L' = F(L), \tag{3}$$

$$x' = X_0' + \cos(\alpha') \cdot L', \tag{4}$$

$$y' = Y_0' + \sin(\alpha') \cdot L', \tag{5}$$

$$M_{x,y} = M'_{x'y'}, \tag{6}$$

where M is the pixel matrix of reconstructed image; M' is the matrix of spherical image pixels; x and y are the current coordinates in the matrix of reconstructed image; x' and y' are the sought-for coordinates in the matrix of spherical image; X_0, Y_0 are the coordinates of reconstructed image centre; X_0', Y_0' are the coordinates of spherical image centre; F is the function describing dependence of the segment length L' on L.

Hence, for each pixel of the matrix M one can find corresponding pixel in the matrix M', if the dependence of segment length L' on L is known. In real equipment calculations according to the formulas (1–5) can be made only once for preliminary calculation of coordinate correspondence $x \rightarrow x'$ and $y \rightarrow y'$. Every newly obtained image is reconstructed according to the formula (6).

Method of function construction *F*

As it was mentioned above, relation of the segment lengths L to L' described by the function F (3) is constant for any image equidistant from the centre point and depends only on characteristics of particular lens. Unfortunately, analytical view of the function F is, as a rule, unknown. Hence, it is necessary to solve the problem of its definition.

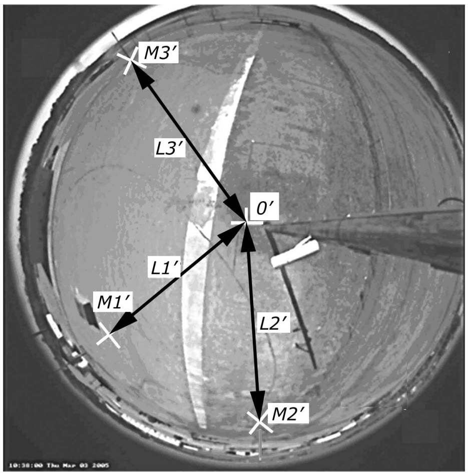
The simplest solution is the method of function recovery F in the known points of the observed surface. For example, if we know exact geometric position of some object on the observed surface, then, knowing its coordinates x' and y' in the spherical image and knowing its position in the reconstructed picture one can define the function F for one fixed length. The mentioned above is illustrated in Fig. 7.

In the spherical image (Fig. 7, *a*) the points $M1'$, $M2'$ and $M3'$ are marked due to the fact that on the territory observed the objects, the distance to which is easily measured (for example, manually), correspond to them. The central point O' is a point over which there is a camera directed vertically down. The distances $L1'$, $L2'$ and $L3'$ are calculated in terms of spherical image in pixels. In the reconstructed image the surfaces are determined by the position of points $M1$, $M2$, $M3$ and O according to their real distribution on the observed surface (see Fig. 7, *b*), after which the distances $L1$, $L2$ and $L3$ are calculated in pixels. For complete construction of the function F it is necessary to connect the experimental points by smooth curve. The most suitable in this case is cubic spline interpolation [2]. The meaning of spline-interpolation consists in the fact that approximation in the form of dependence is performed in every interval between nodes:

$$F(L) = k_3 \cdot L^3 + k_2 \cdot L^2 + k_1 \cdot L + k_0, \qquad (7)$$

where coefficients k_0, k_1, k_2, k_3 are calculated independently for each interval based on the values of L in neighborhood points. As at zero length of the segment at L' in spherical picture we have zero length of the segment corresponding to it in the reconstructed picture, the relationship (7) is written down in the following way:

$$F(0) = 0. \qquad (8)$$



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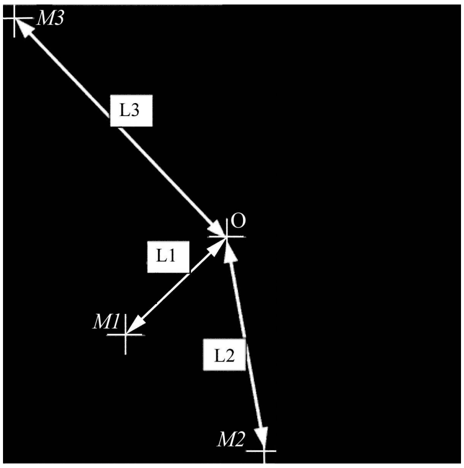

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Fig. 7. *Method of function determination F*

Spline-interpolation provides the equality in the nodes of not only neighbourhood interpolating functions themselves (splines), but also of their first derivatives. Therefore, the result of spline-interpolation looks like smooth function. Note that dependence graph of L' on L (3) will be more exact, if much more preliminary measured points participate in spline-interpolation. In Fig. 8 the example of the obtained dependence of L' on L is demonstrated.

In the given Figure spline-interpolation is performed in eight points including zero point (8). The values of L to L' relationships obtained experimentally are displayed by thick points. The distances that are within the corresponding regions A', B', C' (Fig. 3) and the values corresponding to them in the reconstruction region a, b, c are displayed by the dashed lines. In Fig. 8 it is evident that less C' region of the spherical picture corresponds to c region covering significant part relatively to the image centre in the reconstructed picture, i. e. there is a strong reduction and distortion of information at the edge of circle. Inversely, significant part of the spherical image A' situated closer to the centre of the sphere corresponds to small part a. The view of the function curve F indicates that the magnitude L' is limited, but the magnitude L can be infinitely large (Fig. 8). From the physical point of view it is true, because the magnitude L' is limited by the size of accepted spherical image, whereas, the magnitude L is the distance to the observed object. Since ultra-wide angle lens permits for circular observation from horizon to horizon, the magnitude L can be infinitesimal. However, at restoration of far objects the result of reconstruction will be distorted because all information on observed remote distances is concentrated at edge pixel of spherical image, which is reduced.

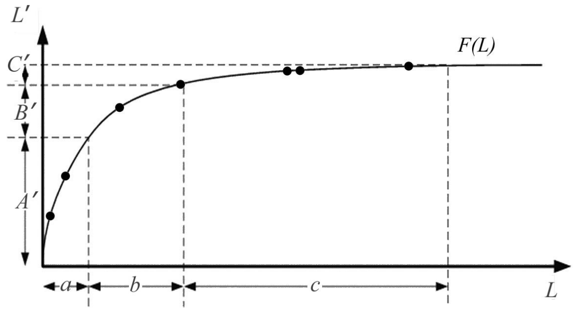


Fig. 8. *Dependence of the length L' on L*

In Fig. 9 the result of reconstruction of the grid image shown before is presented (Fig. 4).

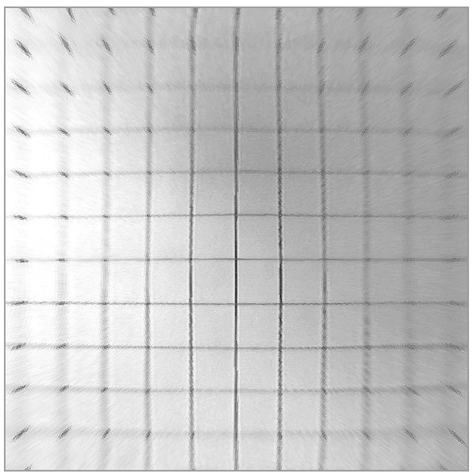


Fig. 9. *Result of reconstruction*

The result of reconstruction of real spherical surface picture is shown in Fig. 10.

It is seen from the Figure that the result of reconstruction (Fig. 10, *b*) of spherical image (Fig. 10, *a*) would be desirable to turn round at small angle in such a way that quadrilateral sides of the zone observed would be parallel by the sides of the image. For this purpose it is enough to modify the expression (2) to the view:

$$\alpha = \operatorname{arctg}\left(\frac{y - Y_0}{x - X_0}\right),$$

$$\alpha' = \alpha + \beta,$$

where β is the arbitrary rotation angle. Moreover, if it is necessary to reduce or to stretch the reconstructed image additionally, for this purpose it is enough to reduce the relations (4, 5) to the following view:

$$x' = X_0' + \cos(\alpha') \cdot L' \cdot Kx,$$

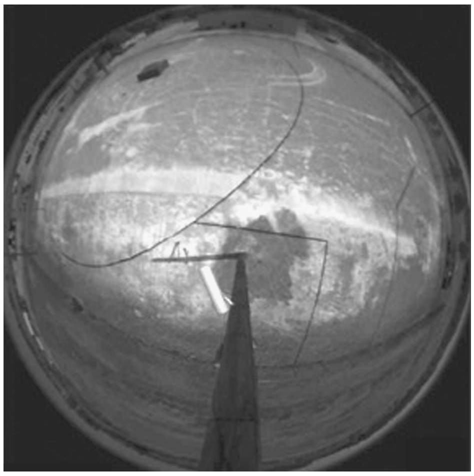
$$y' = Y_0' + \sin(\alpha') \cdot L' \cdot Ky,$$

where Kx and Ky are the reduction coefficient along the X and Y axes respectively.

Thus, one can provide the rotation, reduction or stretching as well as other affine transformations directly in the reconstruction algorithm excluding additional and cost-is-no-object, from calculation point of view, subsequent processing of image.

Conclusion

1. Rapid algorithm of pixel-by-pixel reconstruction of spherical images based on the principle of search for pixel coordinate in the spherical image corresponding to the pixel coordinates in the reconstructed image has been suggested. The algorithm allows for:
   - easy synthesis of rapid algorithm for partial reconstruction desired zones of spherical image without preliminary reconstruction of the whole image surface;
   - different affine transformations at the stage of preliminary calculation of pixel coordinate correspondence, i. e. without additional calculations at the stage of reconstruction. For example, rotation, stretching, mirror image and displacement.
2. The analytical view of the function describing the relation of segment lengths belonging to central lines has been produced using cubic spline-interpolation. The given method can be used independently in similar works on study in characteristics of ultra-wide angle lenses themselves.



a

b

Fig. 10. *Result of reconstruction of real spherical picture*

3. The algorithm of pixel-by-pixel reconstruction for spherical images and the method of semi-automatic calculation of the analytical function F in terms of the spherical image of periodical picture (it is necessary to specify the parameters of the picture) are performed in the programme library in Си language. Besides, in Си language the user's modules for MathCad programme are realised. This allows user to make scientific-practical experiments on processing of similar images directly in MathCad.

REFERENCES

1. Forsite P. Computer vision. Modern approach. – Moscow: «Williams» publishing house, 2004. – 928 p.
2. Rogers D., Adams D. Mathematical bases of computer graphics. – Moscow: Mir, 2001. – 604 p.

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