등거리 스테레오 전방위 렌즈 영상에 대한 위치 측정 알고리즘

Range finding algorithm of equidistance stereo catadioptric mirror

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Choi, young ho

요 약

전방위 렌즈의 단점은 균일하지 않은 해상도에 있다. 등거리 전방위 렌즈는 이러한 단점을 해결하기 위한 새로운 대안으로 볼 수 있으며, 등거리 스테레오 전방위 렌즈는 한 개의 카메라를 통해 스테레오 영상을 획득할 수 있다는 점에서 매우 효율적인 시스템이라 말할 수 있다. 그러나 등거리 스테레오 전방위 렌즈는 단일 등거리 전방위 렌즈에 비해 획득 영상의 크기가 상대적으로 작게 되어 해상도가 낮아진다는 단점이 있다. 정확한 거울의 위치, 카메라 축과 거울 중심과의 정확한 정렬 등의 문제는 정밀도를 높여 해결할 수 있지만, 영상 획득 시 필수적으로 필요한 렌즈의 초점 거리 변화는 피할 수 없게 된다. 본 논문에서는 먼저 초점 거리 변화가 물체의 거리 측정에 미치는 영향을 고찰한 후 스테레오 영상에서 보이는 물체의 시야 각은 두 영상에서 거의 일정하다는 가정하에 실제 초점 거리를 계산하는 방법을 제시한다.

Abstract

Catadioptric mirrors are widely used in automatic surveillance system. The major drawback of catadioptric mirror is its unequal image resolution. Equidistance catadioptric mirror can be the solution to this problem. Even double panoramic structure can generate stereo images with single camera system. So two images obtained from double panoramic equidistance catadioptric mirror can be used in finding the depth and height values of object's points. But compared to the single catadioptric mirror, the image size of double panoramic system is relatively small. This leads to the severe accuracy problem in estimation. The exact axial alignment and the exact mount of mirror are the sources that can be avoided but the focal length variation is inevitable. In this paper, the effects of focal length variation on the computation of depth and height of object' point are explained and the effective focal length finding algorithm, using the assumption that the object's viewing angles are almost same in stereo images, is presented.

☞ Keyword : Catadioptric mirror, Stereo vision, Image matching

1. Introduction

A catadioptric sensor is a sensor that contains mirrors (catoptrics) and lenses (dioptrics). For computer vision applications, catadioptric sensors generally consist of a camera pointed at a convex mirror. They have found many applications in robotics, such as navigation and localization and in automatic surveillance system. Additionally, many of the classical computer vision problems, such as stereo and structure from motion are being studied in the context of these sensors. Furthermore some stereo catadioptric sensors are proposed recently as a replacement of a traditional stereo image acquisition apparatus. In spite of the advantage of full viewing angle, the lack of uniformity of resolution of common traditional catadioptric sensors, which results in the distorted image, leads to the additional image

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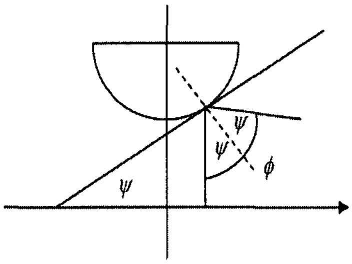
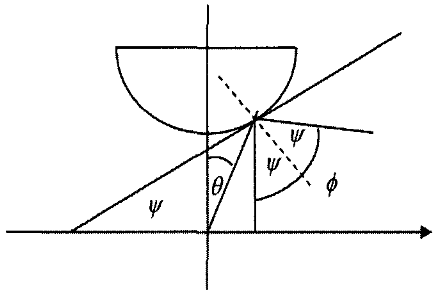
processing endeavor. To overcome this problem, the studies on the design of equiresolution catadioptric sensors have been made recently [5]. In two projection schemes, orthographic and perspective, they derived the equiresolution catadioptric lens's profiles and the former works of Chahl and Srinivasan [2], Conroy and Moore [3] and Ollis et al.[4] are compared using their unified approaches on lens's resolution. The non-equiresolution catadioptric sensor's variation of resolution is explained by the proposed magnification factor. In fact, equiresolution catadioptric sensors can be designed in both orthographic projection scheme and perspective projection scheme. Recently the equiresolution panoramic catadioptric lens with perspective projection has been presented in [1] and furthermore their lens provides stereo panoramic images that can be used in structure-related tasks. That lens in [1] provides successfully two equiresolution panorama images. But their stereo panorama images might to be inadequate to compute the structure information e.g. the depth information. The equiresolution lens that has been designed in orthographic projection scheme doesn't need to satisfy the exact focal distance because of its inherent assumption of the far-apart focal plane from the mirror. But in real circumstances, the orthographic projection scheme is not applicable because of its long distance from the mirror to the camera. The equiresolution in perspective projection scheme can be thought to be adequate and its usefulness has been found easily. In [1], with the very simple unwrapping image processing the acquired catadioptric images can be converted to the realistic panorama images with no severe image distortions. From that result, the equiresolution lens with perspective projection can be said to provide the more superior panorama image with the minimal additional efforts especially in the automatic surveillance applications.

But as noted in [1], their equiresolution catadioptric lens with perspective projection scheme confronted with the errors in determination of structure. The sources of errors in that case can be stated as followings: the axial misalignment of camera with lens, the mismatch of the axial distance from the camera to the mirror and the mismatch of the distance from the camera nodal point to the image sensor with the predetermined values in the design process. Some of the above can be avoided but the latter problem, the mismatch of the distance from the camera nodal point to the image sensor with the predefined values in the design process, can not be avoided even the sophisticated endeavors. This mismatch results from the inherent focusing process of the conventional camera. To cope with this problem, the range finding algorithm has to take account of the variation of camera nodal point. In this paper, the novel range finding algorithm that exploits the effect of camera nodal point's variation on the depth calculation is presented. To find out the depth information of the given point in one image, the counterpart in the other image is to be found. The correspondence between two images has been made by manual selection of points in [1]. In this paper the correspondence of two object's points has been made by line matching method. In section 2, equiresolution catadioptric sensors are explained. In section 3, the stereo equiresolution lens with perspective



〈Fig 1〉 Catadioptric sensor with orthographic projection



〈Fig 2〉 Notation in the perspective case

projection scheme is presented. In section 4, the range finding algorithm of the proposed stereo equiresolution lens in ideal circumstances is presented. The effect of the nodal point's variation is explained and the range finding algorithm is presented in section 5. Section 6 shows the experimental results. Finally, the discussions and conclusions are mentioned in section 7.

2. Equiresolution Catadioptric Lens

2.1 Orthographic projection

Fig. 1 depicts the basic form of a catadioptric sensor modeled by an orthographic projection. The derivation of equiresolution mirror in orthographic projection is carried by computing the infinitesimal magnification factor of the inverse of the projection from the view sphere to the image plane in terms of the cross-section f, and then to require that this quantity be constant. The magnification factor at x can be defined as Eq. (1).

$$m_f(x) = \lim_{\Delta x \to 0} \frac{2\pi(\cos(\phi) - \cos(\phi + \Delta\phi))}{\pi(x + \Delta x)^2 - \pi x^2} \quad (1)$$

Since $\frac{\Delta\phi}{\Delta x} \to \frac{d\phi}{dx} \; as \; \Delta x \to 0$, the following relation can be obtained.

$$m_f(x) = \lim_{\Delta x \to 0} \frac{2\pi\left(\cos(\phi) - \cos\left(\phi + \frac{\Delta\phi}{\Delta x}\Delta x\right)\right)}{\pi(2x\Delta x + \Delta x^2)} = \frac{\sin(\phi)}{x}\frac{d\phi}{dx} \quad (2)$$

Using the fact that $\phi = 2\tan^{-1}(f'(x))$, we have

$$m_f(x) = \frac{4f'(x)f''(x)}{x(1 + f'(x)^2)^2} = K \quad (3)$$

2.2 Perspective projection

Fig.2 is the notation for deriving the differential equation in the perspective case. Assume that the center of projection of the camera is placed at the origin and that a ray of light entering the camera is incident with the mirror at (r,θ). Then the slope of the tangent line at (r,θ) is Eq. (4).

$$m = \frac{dy}{dx} = \frac{\frac{dy}{d\theta}}{\frac{dy}{d\theta}} = \frac{\frac{dr}{d\theta}(\cos\theta - r\sin\theta)}{\frac{dr}{d\theta}(\sin\theta + r\cos\theta)} \quad (4)$$

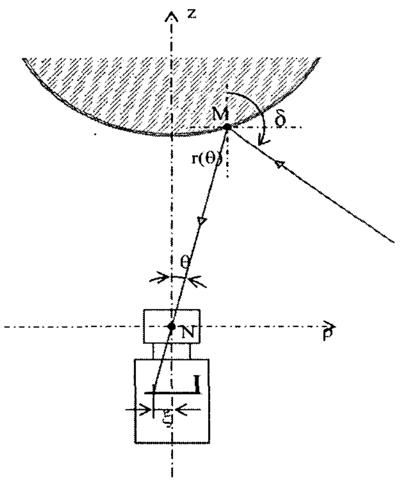
Solving this equation for $\frac{dr}{d\theta}$ gives the following equation.

$$\frac{dr}{d\theta}=\frac{r\left(\sin\theta-\cos\theta\tan\left(\frac{\theta-\phi}{2}\right)\right)}{\left(\cos\theta-\sin\theta\tan\left(\frac{\theta-\phi}{2}\right)\right)} \tag{5}$$

Solving for ϕ in Eq. (6) and substituting into equation (5) gives a differential equation that may be solved numerically.

3. Stereo Equidistance Catadioptric Lens

Typically catadioptric panoramic lens is composed of a standard camera lens and a panoramic mirror. As shown in Fig. 3, the symmetry axis of the rotationally symmetric panoramic mirror coincides with the optical axis of the camera and the nodal point of the camera lens lies at the origin of the coordinate system. The incident ray with a zenith angle δ is reflected by the panoramic mirror M and



⟨Fig 3⟩ The schematic diagram of

enters the camera lens with a zenith angle θ. Scenes from full 360° directions are captured in the image sensor I in a ring shape and this image can be subsequently unwarped to give viewer-friendly full 360^0 panorama scene.

3.1 Equidistance mirror profile derivation.

In [1], a stereo equiresolution catadioptric sensor is proposed. The design process is same as the above mentioned approach. The constraint equation used to model the mirror' profile is Eq.(7).

$$\frac{d(\tan\theta)}{d\delta}=C\ ,\ \tan\phi=\frac{d\rho}{dz} \tag{7}$$

The above Equation can be expressed in terms of the spherical coordinates,

$$\cot\phi=\frac{r'\cos\theta-r\sin\theta}{r'\sin\theta+r\cos\theta} \tag{8}$$

where r' is the derivative with respect to θ.

The radial and the angular coordinates can be separated as given by,

$$\frac{r'}{r}=\frac{\sin\theta+\cot(\phi(\theta))\cos\theta}{\cos\theta-\cot(\phi(\theta))\sin\theta} \tag{9}$$

The distance to the mirror point is given as

$$r(\theta)=r(\theta_i)\exp\left[\int_{\theta_i}^{\theta}\frac{\sin\theta'+\cot(\phi(\theta'))\cos\theta'}{\cos\theta'-\cot(\phi(\theta'))\sin\theta'}d\theta'\right] \tag{10}$$

where θ_i is the lower bound of the integration with a corresponding distance given as $r_i\equiv r(\theta_i)=\sqrt{\rho_i^{\,2}+z_i^{\,2}}$.

The law of specula reflections is given by

$$\phi = \frac{\delta + \theta}{2} \tag{11}$$

In the equidistance projection scheme, $\tan\theta$ is given as a linear function of δ as given by

$$\tan\theta = \beta\delta + \psi \tag{12}$$

where β and ψ are constants.
Two constants can be determined as

$$\beta = \frac{\tan\theta_2 - \tan\theta_1}{\delta_2 - \delta_1} \quad \text{and} \quad \psi = \frac{\delta_2 \tan\theta_1 - \delta_1 \tan\theta_2}{\delta_2 - \delta_1} \tag{13}$$

The Eq. (10) can be used with Eq. (13) to obtain the desired mirror profile.

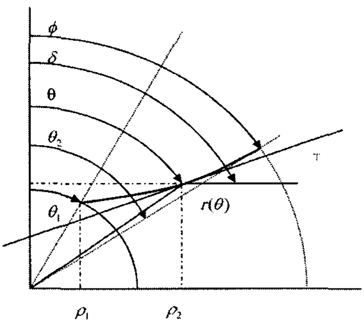
$$\phi(\theta) = \frac{\tan\theta - \psi + \beta\theta}{2\beta} \tag{14}$$

The distinguished aspect of that design is that the proposed system provides the equiresolution stereo images with perspective projection scheme. Equiresolution in orthographic projection eventually provides the non-equiresolution images if the conventional perspective camera is used as the dioptric component. Fig. 4 shows the schematic diagram illustrating specular reflections in the panoramic mirror along with the variables used in analyzing the mirror profile. Fig. 5 depicts the division of the image sensor for the inner and outer panoramic mirrors. The used CCD camera sensor has a dimension of 15*15mm with a 2048 x 2048 pixels. The distance from the camera nodal point to the image sensor plane is approximately equal to the focal length f=24mm of the camera lens. The axial distance from the camera nodal point to the outer rim of the inner panoramic mirror is set as 240mm, while the outer radius of the inner panoramic mirror is set as 40mm.

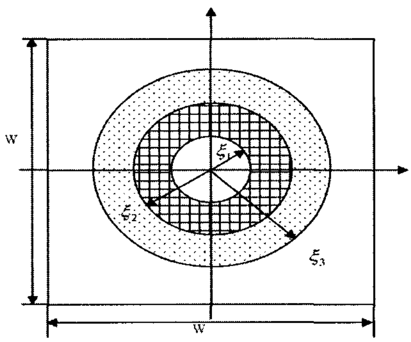
The profile of the equiresolution stereo panoramic lens with perspective projection scheme is shown in Fig. 6. The inner and outer mirror profiles are separately fitted with Nth order polynomial as given by

$$h(\rho) = \sum_{n=0}^{N} C_n \rho^2 \tag{15}$$

where $h(\rho) = \max(z) - z$



⟨Fig 4⟩ Schematic diagram illustrating specular reflections in the panoramic mirror



⟨Fig 5⟩ Division of image sensor

〈Table 1〉 Coefficient of mirror profile

Variable	Inner mirror	Outer mirror
C0	64.065800	11.785600
C1	3.423100	0.775000
C2	0.069800	0.001664
C3	0.000442	0.000176

In [1], the mirror profiles are chosen as Table 1.

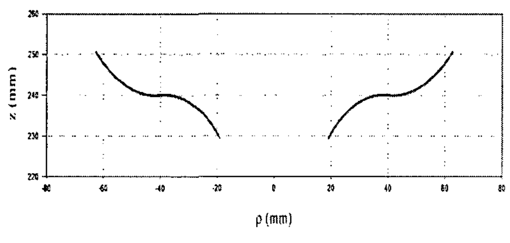
Fig. 7 shows the calculated input ray directions corresponding to a pixel in the sensor. The distance in the image sensor is calculated assuming that the distance from the nodal point to the image plane is identical to the camera focal length f. As can be seen, the mirror profile in [1] has a perfect equiresolution projection scheme.

4. Rangefinder algorithm in Stereo Equiresolution catadioptric sensor

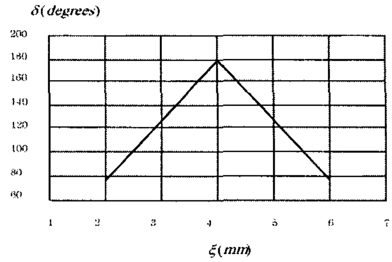
4.1 In case of known correspondence

Fig. 8 shows a schematic diagram of the double panoramic imaging system for the determination of the distance and the height of an object point.

From Fig. 8 the following relationships can be derived.



〈Fig 6〉 Equidistance double panoramic mirror profile



〈Fig 7〉 Projection scheme of Equidistance double panoramic mirror

$$r_1 \cos\theta_1 = h - d\cot\delta_1 + \rho_1 \cot\delta_1 \quad (16)$$

$$r_2 \cos\theta_2 = h - d\cot\delta_2 + \rho_2 \cot\delta_2 \quad (17)$$

From these two equations, the horizontal distance and vertical height can be determined as

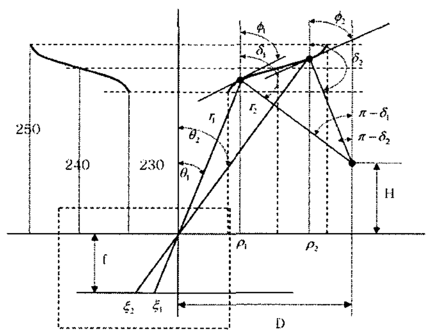
$$D = \frac{(\rho_2 \cot\delta_2 - \rho_1 \cot\delta_1) - (z_2 - z_1)}{\cot\delta_2 - \cot\delta_1} \quad (18)$$

and

$$H = \frac{(z_1 \cot\delta_2 - z_2 \cot\delta_1) + (\rho_2 - \rho_1)\cot\delta_2 \cot\delta_1}{\cot\delta_2 - \cot\delta_1} \quad (19)$$

The zenith angle for the reflected ray is given as

$$\theta = \tan^{-1}\left(\frac{\xi}{f}\right) \quad (20)$$



〈Fig 8〉 Schematic diagram illustrating the depth determination algorithm

By measuring the two corresponding distance ξ_1 and ξ_2 for a common object point in the image sensor, the position of the object point can be determined using the above mentioned equations. The image sensor is square in shape with one side measuring 15mm and containing 2048*2048 pixels. The distance from the camera nodal point to the image sensor is assumed the same as the camera focal length. From the pixel position ξ, the reflection angle is calculated as

$$\theta = \tan^{-1}\left(\frac{15}{2f}\frac{\xi - 1024}{1024}\right) \tag{21}$$

From the calculated θ, the zenith angle δ for the incident ray cab be given by

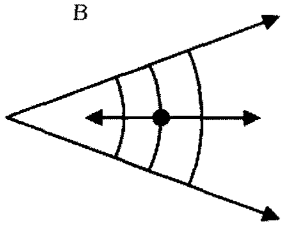
$$\delta = 2\cot^{-1}\left(\frac{dz}{d\rho}\right) - \theta \tag{22}$$

Using the following relation, δ can be calculated.

4.2 Finding the correspondence

4.2.1 Line matching

To calculate the object's depth and height, the correspondence of the object's point ought to be found. The conventional matching algorithms are not applicable to our case because of the difference of two image's dimension



⟨Fig 9⟩ Image slice used in line matching

i.e. the outer image is larger than the inner image. Furthermore the inner image's direction is opposite to the outer image. Notice that the equiresolution property is restricted to the ρ direction. Fig. 9 shows the relationship of two images. The conventional block-based matching methods that use the neighborhood pixels in finding the correspondence require the additional area transformation process i.e. affine transformation. That results the poor image quality. So we use the line matching method explained as following. The line matching method needs the polar to rectangular coordinate transform. The search range is confined to the angular direction, because the panoramic mirror gives the stereo images that are not deviated in angular direction. Image slice in Fig. 9 shows that the required search direction.

- for a given pixel of inner[outer] image
- calculate its radius(r) and angle(s) in its image plane
- select the neighborhood pixels according to the predefined Δr and Δs around of a given pixel

$$z = \max(z) - h(\rho) = \begin{cases} 249.968595 - (64.065800 - 3.4231\rho + 0.069800\rho^2 - 0.000442\rho^3) \rightarrow \textit{Inner mirror} \\ 249.968595 - (-11.785600 + 0.775\rho + 0.001664\rho^2 - 0.000176\rho^3) \rightarrow \textit{Outer mirror} \end{cases}$$

$$\frac{dz}{d\rho} = \begin{cases} (3.4231 - 0.1396\rho + 0.001326\rho^2) \rightarrow \textit{Inner mirror} \\ (-0.775 - 0.003328\rho + 0.000528\rho^2) \rightarrow \textit{Outer mirror} \end{cases} \tag{23}$$

$$d(r_c, s_c) = \sum_{r=-\frac{\Delta r}{2}}^{\frac{\Delta r}{2}} \sum_{s=-\frac{\Delta s}{2}}^{\frac{\Delta s}{2}} \left(I_{inner[outer]}(r_i + r, s_i + s) - I_{outer[inner]}(r_c + r, s_c + s) \right)^2 \quad (24)$$

- for every candidate location on outer[inner] image
- select the neighborhood pixels according to the Δr and Δs around of that location
- compute the distances on all candidate locations
- choose the location that gives the minimum distance value as the correspondence pair

The following distance measure can be used effectively.

The above mentioned procedure can be effectively converted by the conventional rectangular MSE matching procedure on the unwrapped image. Fig. 10 represents the parameters used in polar- to-rectangular unwrapping procedure.

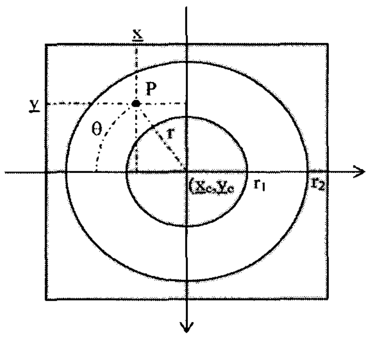
5. The Errors in finding the depth

5.1 Misplacing of the nodal point

In [1], it was found that the result is strongly dependent on the exact value of the focal length and the axial misalignment. The difficulty of the exact value of the focal length results from the fact that the focusing processing to acquire the more sharpened image is inevitable. To cope with the problem that there is an offset in the distance from the camera nodal point to the mirror surface, the following modification on the height of the mirror was used in [1].

$$z_1 = r_1 \cos\theta_1 + \Delta \quad (25)$$

But the above modification turns out to be inappropriate. The error in range finding process can not be fully explained by means of the offset in the distance from the camera nodal point to the mirror surface. In this paper, the alternative modeling on the variation of focal length is presented to acquire the more accurate D and H values from the correspondences of the object's points. The Fig. 11 shows the effects of focal length variation on the calculation of degree theta. Although the location of mirror that relates to the exact z value could be adjusted, the focal length variation is inevitable. The environmental light condition is to be changed occasionally and the lens aperture size is to be adjusted to control the light intensity. This inevitably results in the focal length variation in conventional perspective camera system.



⟨Fig 10⟩ The polar-to-rectangular transform

5.2 Proposed range finding algorithm

Fig. 11 illustrates the schematic diagram for the proposed range finding algorithm. Once the correspondence of the object's point in two panoramic images has been found, from those values the overall depth and height values are determined by the design stage formulae. When the focal length is shortened by 10 percent of the originally assumed focal length, the value of theta is also decreased by 10 percent approximately. Equidistance mirror property explains well the above mentioned relationship. The outer and inner catadioptric mirrors cover the range of the incident rays from 70 degree to 180 degree. The error of 10 percent in focal length leads to about 10 percent deviation of the estimated incident ray from the correct incident ray. In our system, 10 percent deviation of the incident ray means 11 degree deviation. This leads to the severe error in determination of D and H values. There are two possible approaches to find out the exact f value. In the first method, the size of the actual diameter of the acquired image can be used to find the exact focal length. The other method is explained as follows. In Fig. 11, the correspondences of two object points are determined using the line matching algorithm. ξ_{i1} represents the pixel location of object P_i on the inner image plane. ξ_{i2} represents the pixel location object P_i .on the outer image plane. ξ_{i1} and ξ_{i2} are the correspondence of object P_i. The pixel distance from ξ_{21} to ξ_{11} correspond to the range of the incident ray originated from object 1 to the incident ray originated from object 2. Except the special case, the pixel distance from ξ_{21} to ξ_{11} is not equal to the pixel distance ξ_{22} to ξ_{12}. Only if the line extending the object point 1 and the object point 2 is tangent to the tangential plane of the mirror, the above two pixel distances can be equal. The equidistance property can not be applied to the depth and height determination process directly because of the randomly chosen objects points. Fig. 12 shows the detailed view of the image plane and the estimated object points. Given four object points, ξ_{21}, ξ_{11}, ξ_{22} and ξ_{12}, one of the two image planes with focal length f and $f+\Delta f$ can be chosen to the more correct image plane using the object's view angle criteria. We can consider the line extending the given two point P_i.and ,P_j. The rays in this range are reflected on the inner mirror and the outer mirror simultaneously. Object's view angle in the inner[outer] image plane is defined as Eq. ??

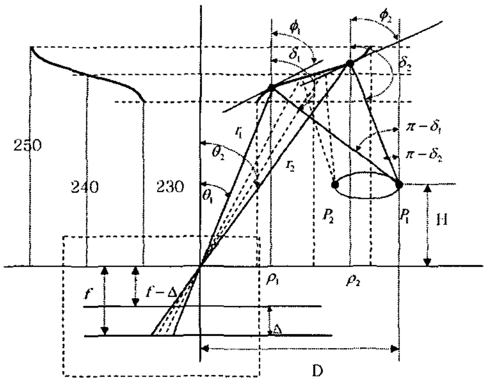
$$
\begin{aligned}
&VA^{f}_{inner} = \left[\theta^{1}_{inner}, \theta^{2}_{inner}\right]_{using\ focal\ length\ f} \\
&VA^{f}_{outter} = \left[\theta^{1}_{outter}, \theta^{2}_{outter}\right]_{using\ focal\ length\ f} \\
&VA = VA^{f}_{inner} \cap VA^{f}_{outter} \\
&VA_{normalizadvalue} = \frac{norm(VA)}{\left(\frac{\left(norm(VA^{f}_{inner}) + norm(VA^{f}_{outter})\right)}{2}\right)} \\
&where\ norm(VA)\ is\ defined\ as\ follows \qquad (26) \\
&norm(VA) = fabs(\theta^{1} - \theta^{2})
\end{aligned}
$$

The above VA reaches at its maximum value when the correct focal length is chosen. In fact, this decision is equivalent to find out the correct boundary between the inner image plane and the outer image plane. The overall range finding algorithm is as follows.

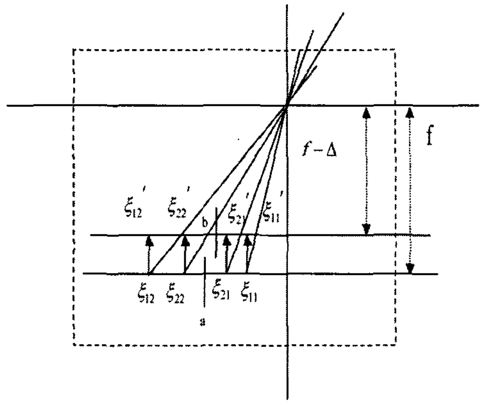
· Perform the image matching process between the inner and the outer image for the given object's two points

· Exact focal length determination

· let $f_{final} = f_{the\ value\ determined\ at\ design\ stage}$, calculate



〈Fig 11〉 The schematic diagram showing the proposed range finding algorithm



〈Fig 12〉 Detailed view of Fig. 11

$VA_{normalization}|_{f_{final}}$

· set $\Delta f = 0.1f$

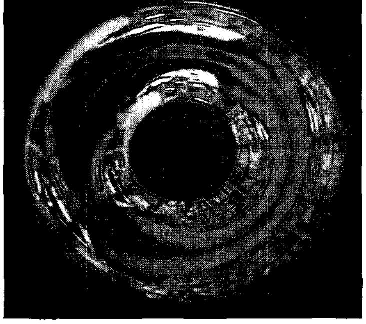
· calculate $VA_{normalization}|_{f_{final}+\Delta f}$ and $VA_{normalization}|_{f_{final}-\Delta f}$

. *set* $f_{final} = f$ *that gives the greatest* $VA_{normalization}$

· stop when $VA_{normalization}|$ is decreased.

· Using the modified focal length value, calculate D and H values

In Fig. 12, a and b is the boundary between the inner and outer image. The pixel distances estimated based on the wrong focal length, i.e. $f-\Delta$, results in the wrong estimation of the pixel distances.

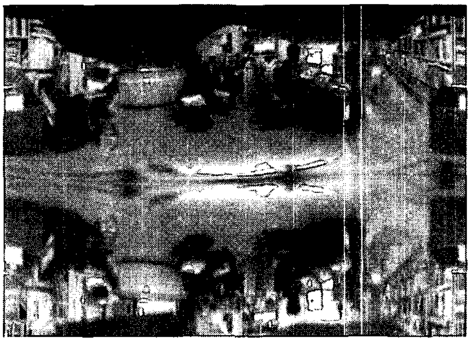


〈Fig 13〉 Captured image

6. Experiments

6.1 Image acquisition

The equidistance catadioptric mirror's focal



〈Fig 14〉 Unwrapped image

〈Fig 15〉 Stereo equidistance images

length is 24mm. Fig. 13 is a captured image using the camera and Fig. 14 is the panorama image after the unwrapping. Fig. 14 shows the captured image is stereo and the direction is opposite.

6.2 Line matching

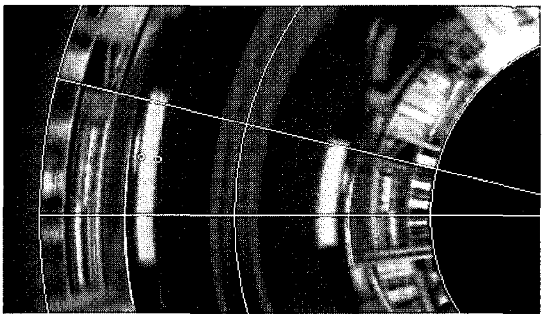
Fig. 16 shows the correspondence process. Two arbitrary object's points are chosen manually. Fig. 17 shows the matching result. As seen in Fig. 16 and Fig. 17, the image resolution is not uniform. This results from the mirror's relatively large profile variation to the distance from camera nodal point to the mirror surface. For the good matching, the prominent image points are selected. The pixel distances of four points form the image center are 746, 718, 443 and 472 respectively. The range finding starts from these four estimated pixel distances. So the accurate pixel location determination is very important and this depends on the correct image center localization. The center of image is located manually. The used matching criterion is MSE. For a given pixel point, 10-pixel angular neighborhood and 5-pixel radius neighborhood pixels are used in calculating MSE criterion on the every search area pixel location. The search area has been chosen as 1-pixel angular width and 40-pixel radius width.

6.4 Focal length modification and range finding

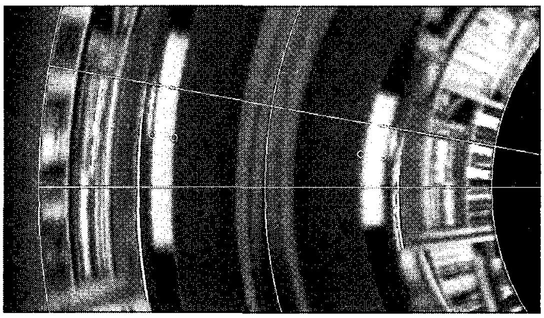
The experiment has been carried out using the same configurations as in [1]. The used value of focal length is 24.0mm and the used value of delta is 2mm. Within 20 iterations, the obtained results are better than that of in [1]. Fig. 5 shows the sample estimation of depth and height. The following equation is used to find out theta value corresponding to the object's points. From this theta value respective delta values can be acquired and the proposed VA(two object's view range) has been computed. Finally, the resulting D and H values are obtained.

$$\theta = \tan^{-1}\left(\frac{15}{2f}\frac{\xi - 1024}{1024}\right) \tag{26}$$

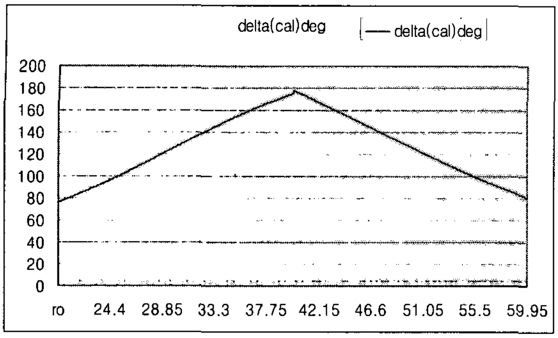
Fig. 18 shows the used delta values that are calculated using the profile function expressed by the polynomial with 4 coefficients. Fig. 19 shows the focal length modification process. In Fig. 19, the normalized VA values



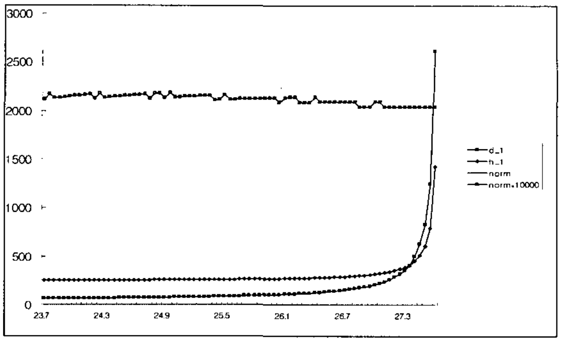
〈Fig 16〉 Two image-points used in line matching



〈Fig 17〉 Matching result

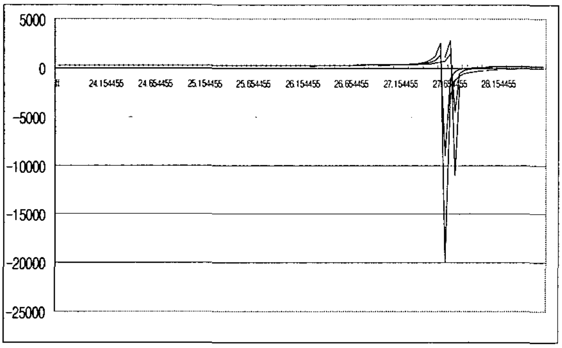


〈Fig 18〉 Delta value



〈Fig 20〉 Detailed view of Fig. 19

are not readable. This figure shows that the wrong focal length values can lead to the wrong determination of D and H. In Fig. 20 the normalized VA values are depicted using the magnified values by 10000. In Fig. 20, the starting focal length value was 24mm. Contrary to the case of Fig. 19, the proposed focal length modification algorithm confines the range of useful focal length values to the interval from 24mm to 27.3mm. Furthermore, the maximum normalized VA value of 25.1 gives the reasonable D and H values. The correct focal length value can be obtained easily. The real D and H values of the object's point were 150mm and 300mm.



〈Fig 19〉 The variation of D and H values according to focal length values

7. Discussions and Further researches

The proposed double-panoramic equiresolution catadioptric lens with the wide vertical field of view of 110 degrees can determine 3-D location of the objects when the correspondence has been determined. But the accuracy depends on the correct focal length value. In real circumstances, the focal length often varies to achieve the more focused image acquisition. In this paper, the new focal length modification algorithm which uses the characteristics of variation of the object's view angles has been presented. The proposed algorithm provides the better results than the original rangefinder algorithm in [1]. From the experiments, we have concluded that the mirror profile was not manufactured correctly. So the estimated D and H values do not coincide with the real D and H. In this paper, the validity of the proposed focal length modification method has been tested using the relative distance of two object's point. Furthermore, Equidistance catadioptric mirror don't have the single view point property, the single view point mirrors can be easily applied to many computer vision applications with their concise epipolar geometric structure. So the study and design of the single view point double panoramic catadioptric mirrors has to be carried out soon.

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