

The AUV Location and Location Error Analysis Based on Binocular Stereo Vision

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Abstract: In the AUV binocular vision navigation, in order to improve the AUV positioning accuracy, optimizing the stereo vision imaging system structure and weighted least-square method is proposed. The principle of AUV location is analyzed, and that the AUV location accuracy depends on the measurement precision of the three dimensional space point is proposed. Based on the analysis of stereo vision measurement principle, it is put forward that the baseline, the focal length, and the object distance directly affect the stereoscopic vision measurement precision, and mathematical relation model was established for the measurement error. The simulation results show that the model can optimize stereo vision system structure and imaging parameters, and the positioning accuracy of AUV can be effectively controlled. Because measurement error of space point is different with the imaging position, the weighted least squares method is proposed. Measurement data is selectively used according to the measurement error, the positioning. An accuracy of AUV is improved. *Copyright © 2013 IFSA.*

Keywords: AUV autonomous location, Binocular stereo vision, Three dimensional measurement error, Error mathematical model, Weighted least squares method.

1. Introduction

In the AUV autonomous navigation, AUV positioning accuracy is affected by the accuracy of the landmark measurement and location estimation method. In the stereo vision measurement system, the system parameter of the camera: optical axis angle of cameras, focal length, object distance, and baseline distance directly affects the measurement error. So before measurements start, it is necessary to optimize system structure.

For the stereo vision system structure, Yan Shuhua *et al.* [1] derived parameters relationship between distance resolution, detection range, detection distance, and the baseline distance in the parallel stereoscopic parallax method, which can be

used to optimize the structure parameters; Zhu Xiaoming *et al.* [2] establish mathematical model of the double CCD stereo vision system according to geometrical imaging principle, and comprehensive analysis three parameters relationship between the baseline distance, the object distance and the viewing distance, which can guide for stereo vision system. Yan Long *et al.* [3] research photogrammetry theory and binocular stereo vision measuring system, analyze measurement accuracy of axis convergent structure, which can estimation measurement error according to the camera parameters, baseline length, distance with the measurement precision in the project.

The analysis [4, 5] of the stereo vision system parameters are interrelated, to some extent, which

gives the optimization analysis, but did not give the analysis of the specific conditions. Based on the analysis of parallel stereo vision measurement principle, with one of the factors as the variables, optimization procedure of concrete and feasible is proposed, it is easy to determine the optimal structural parameters. With which the measurement accuracy of the space point is better, and the AUV accuracy can be ensured.

2. AUV Locating Principle Based on Stereo Vision

The motion trajectory of AUV is determined by the spatial rotation matrix and translation matrix, including six parameters, so to solve the motion trajectory of AUV, six independent equations, which needed are established. Two equations are determined with one corresponding space point, so at least three corresponding space points are required. Space point coordinates can be located with observed disparity on the same target from binocular stereo vision, based on triangulation principle.

2.1. This is a Subtitle Example

AUV navigates with a certain depth from the sea level, two parallel view axis of the camera look down seabed. Based on the principle of stereo vision, the camera of AUV observes the same goal from two viewpoints, then gets two three-dimensional coordinates m , m' of space point P , then the AUV is located with position relation of two view points through coordinate transformation.

m is the coordinates of three-dimensional point P in Euclidean space, m' is the coordinates of three-dimensional point P after the AUV movement, R is the rotation matrix of AUV, t is the translation vector, taking into account the noise data η_i [6, 7]:

$$m'_i = Rm_i + t + \eta_i \quad (1)$$

There are 3 freedom degrees of R , there are 3 freedom degrees of t , the movement can be decided at least with three pair noncollinear matching points. Due to noise or measurement error η_i , which is described by a scalar w_i , motion (R, t) is estimated by the function minimization:

$$f(R, t) = \sum_{i=1}^n w_i \|m'_i - (Rm_i + t)\|^2 \quad (2)$$

If constraints are ignored between factors of rotation matrix R , x is a vector of 12 dimensional

and A_i is a matrix of 3×12 dimensional, $0^T = (0, 0, 0)$ is a zero vector of 3 dimensional.

$$x = (r_{11}, r_{12}, \dots, r_{33}, t_1, t_2, t_3)^T$$

$$A_i = \begin{bmatrix} m_i^T & 0^T & 0^T & 1 & 0 & 0 \\ 0^T & m_i^T & 0^T & 0 & 1 & 0 \\ 0^T & 0^T & m_i^T & 0 & 0 & 1 \end{bmatrix}$$

Then the equation (2) changes into:

$$m'_i = A_i x \quad (3)$$

Motion matrix is obtained with the least squares method when the first order of $F(R, t)$ derivative to zero

$$x = \left(\sum_i A_i^T A_i \right)^{-1} \left(\sum_i A_i^T m'_i \right) \quad (4)$$

Equation (4) is the motion relationship between AUV two viewpoints, in order to make $\left(\sum_i A_i^T A_i \right)$

reversible, at least four pairs of spatial coordinates of the two viewpoints is needed.

From the principle of the AUV positioning, it is known that positioning errors of AUV motion is mainly caused by the measurement noise. If the measurement noise is zero mean, and variance is random vector of R , the least squares estimator is unbiased estimation. The array of the mean square error:

$$E[\tilde{x}\tilde{x}^T] = (A^T A)^{-1} A^T R A (A^T A)^{-1}, \quad (5)$$

where $\tilde{x} = x - \hat{x}$.

The mean square error reflects the deviation degree between the estimation value of AUV positioning and the true value, which value is related with variance R of the spatial point measurement noise. If the measurement noise error is bigger, and the AUV positioning error is bigger too, so the measurement error need to control, and the measurement error can be controlled from the imaging structure.

2.2. Three-Dimensional Measurement Principle of Stereo Vision

Space three-dimensional point is measurable when it is respectively observed in the two viewpoints by camera, namely the stereo vision. When two cameras is laid with relative fixed position and orientation, observe the same scene from two

viewpoints with different angles, and acquire the image at different view angle. The 3D information of target is calculated based on triangulation principle with the disparity.

For the parallel binocular vision, the focal length of two cameras are the same, the internal parameters are the same, and the two camera optical axis parallel to each other [8]. X axes is of coincidence, Y axes parallel to each other. Therefore, the first camera shifts along the X axis for a distance and coincide with the second camera. As shown in Fig. 1.

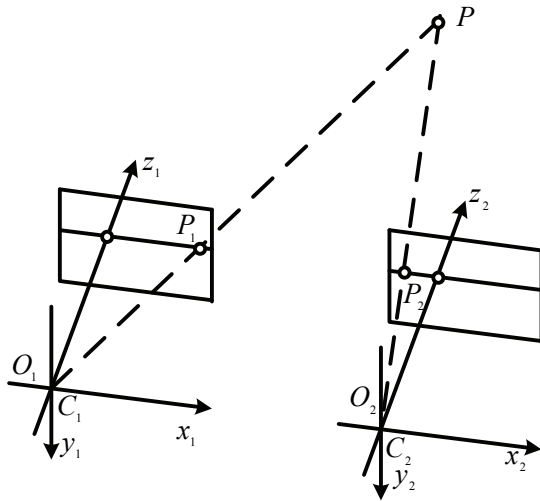


Fig. 1. Parallel binocular imaging model.

$O_1x_1y_1z_1$ and $O_2x_2y_2z_2$ are coordinate system of two cameras respectively, and there is only a translational in axis direction for the two camera coordinate system [9]. The translation distance is recorded as b , also known as the baseline length, i.e. the distance between the left and right camera optical center, which can be obtained with camera calibration. The internal parameters of two cameras are the same, (u_0, v_0) are the center pixel coordinates of the image, f is the focal length (unit: mm). Because the focal length of pixel expressed is need in the following processing, two parameters α_x, α_y is defined. $\alpha_x = -fk_x$, $\alpha_y = -fk_y$, which are the focal length respectively in the horizontal and vertical pixels unit, k_x and k_y are valid pixels number per mm along the u axis and the v axis.

For any point P in the space, its coordinates respectively are (x_1, y_1, z_1) and $(x_1 - b, y_1, z_1)$ in the coordinates system C_1 and C_2 , P_1, P_2 are the image points in left and right camera image plane [10-12].

Coordination m of P point is available with the

projection proportion relationship:

$$\begin{cases} x_1 = \frac{b(u_1 - u_0)}{u_1 - u_2} \\ y_1 = \frac{b\alpha_x(v_1 - v_0)}{\alpha_y(u_1 - u_2)} \\ z_1 = \frac{b\alpha_x}{u_1 - u_2} \end{cases} \quad (6)$$

Among them, $u_0, v_0, \alpha_x, \alpha_y$ are the intrinsic parameters of the camera, which can be obtained with the camera calibration. (u_0, v_0) is the center coordinates of the left image. (u_1, v_1) is the pixel coordination of P point in the left image plane. (u_1, v_1) is the pixel coordination of P point in the left image plane.

3. Analysis AUV Locating Accuracy of Stereo Vision

3.1. Analysis Measurement Accuracy of Stereo Vision

The space point coordinates are related with parallax, which also can be said that the depth information is related with parallax, and x, y coordinates are related with depth. following measurement precision of 3D coordination (x, y, z) of the space target point are calculated.

Depth information is associated with parallax, if the disparity $|u_1 - u_2|$ is not accurate, such as the corresponding point is of deviation, or feature points location is of deviation, which will cause measurement error in the distance z_1 , at the same time, in the x_1, y_1 . Assuming that the measurement error of u_1 is δu_1 , the measurement error of u_2 is δu_2 , the measurement error of v_1 is δv_1 , then

$$\frac{\partial x_1}{\partial u_1} = \frac{b(1 - u_1) + bu_0}{(u_1 - u_2)^2}$$

$$\frac{\partial x_1}{\partial u_1} = \frac{b(u_1 - 1) - bu_0}{(u_1 - u_2)^2}$$

$$\frac{\partial y_1}{\partial u_1} = \frac{-b\alpha_x(v_1 - v_0)}{\alpha_y(u_1 - u_2)^2}$$

$$\frac{\partial y_1}{\partial u_2} = \frac{b\alpha_x(v_1 - v_0)}{\alpha_y(u_1 - u_2)^2}$$

$$\frac{\partial y_1}{\partial v_1} = \frac{b\alpha_x}{\alpha_y(u_1 - u_2)} \quad \Delta x_1 = \frac{\sqrt{2}z^2}{b\alpha_x^2} \sqrt{(1-u_1)^2 + u_0^2} \quad (13)$$

$$\frac{\partial z_1}{\partial u_1} = \frac{-b\alpha_x}{(u_1 - u_2)^2} \quad \Delta y_1 = \frac{z^2}{b\alpha_x\alpha_y} \sqrt{2(v_1 - v_0)^2 + \left(\frac{z_1}{b\alpha_x}\right)^2} \quad (14)$$

$$\frac{\partial z_1}{\partial u_2} = \frac{b\alpha_x}{(u_1 - u_2)^2} \quad \Delta z_1 = \frac{\sqrt{2}z^2}{b\alpha_x} \quad (15)$$

Synthesis the influential factors, then the measurement accuracy in the x direction is Δx_1 :

$$\begin{aligned} \Delta x_1 &= \sqrt{\left(\frac{\partial x}{\partial u_1} \delta u_1\right)^2 + \left(\frac{\partial x}{\partial u_2} \delta u_2\right)^2} = \\ &= \frac{b}{(u_1 - u_2)^2} \sqrt{[(1-u_1) + u_0]^2 (\delta u_1)^2 + [(u_1 - 1) - u_0]^2 (\delta u_2)^2} \end{aligned} \quad (7)$$

The measurement accuracy in the y direction is Δy_1 :

$$\begin{aligned} \Delta y_1 &= \sqrt{\left(\frac{\partial y}{\partial u_1} \delta u_1\right)^2 + \left(\frac{\partial y}{\partial u_2} \delta u_2\right)^2 + \left(\frac{\partial y}{\partial v_1} \delta v_1\right)^2} = \\ &= \frac{b\alpha_x}{\alpha_y(u_1 - u_2)^2} \sqrt{(v_1 - v_0)^2 [(\delta u_1)^2 + (\delta u_2)^2] + (u_1 - u_2)^2 (\delta v_1)^2} \end{aligned} \quad (8)$$

The measurement accuracy in the z direction is Δz_1 :

$$\begin{aligned} \Delta z_1 &= \sqrt{\left(\frac{\partial z}{\partial u_1} \delta u_1\right)^2 + \left(\frac{\partial z}{\partial u_2} \delta u_2\right)^2} = \\ &= \frac{b\alpha_x}{(u_1 - u_2)^2} \sqrt{(\delta u_1)^2 + (\delta u_2)^2} \end{aligned} \quad (9)$$

Taking into account the relationship between ranging accuracy and baseline length, object distance, and the focal length, the z in the expression (6), (7), (8) is substituted with expression (5):

$$\Delta x_1 = \frac{z^2}{b\alpha_x^2} \sqrt{[(1-u_1) + u_0]^2 (\delta u_1)^2 + [(u_1 - 1) - u_0]^2 (\delta u_2)^2} \quad (10)$$

$$\Delta y_1 = \frac{z^2}{b\alpha_x\alpha_y} \sqrt{(v_1 - v_0)^2 [(\delta u_1)^2 + (\delta u_2)^2] + \left(\frac{z_1}{b\alpha_x}\right)^2 (\delta v_1)^2} \quad (11)$$

$$\Delta z_1 = \frac{z^2}{b\alpha_x} \sqrt{(\delta u_1)^2 + (\delta u_2)^2} \quad (12)$$

The pixel size is 0.01mm, $\delta u_1 = \delta u_2 = 1$ pixel, then expression (9), (10), (11) change into:

When the camera pixel number is 1024*1024, object length is 5 m, the baseline distance is 50 cm, the focal length range was 1-30 mm, then the x measurement error changes with focus and imaging position as shown in Fig. 2 (a), the y measurement error changes with focus and imaging position as shown in Fig. 2 (b), the z measurement error changes with the focal length as shown in Fig. 2 (c) shows. It can be seen from Fig. 2, when the focal length is less than 5 mm, the error grows very quickly, in order to reduce the error, a telephoto lens is needed, but lens is longer, field of view is smaller. In order to take into account the view field, the 10 mm lens is selected.

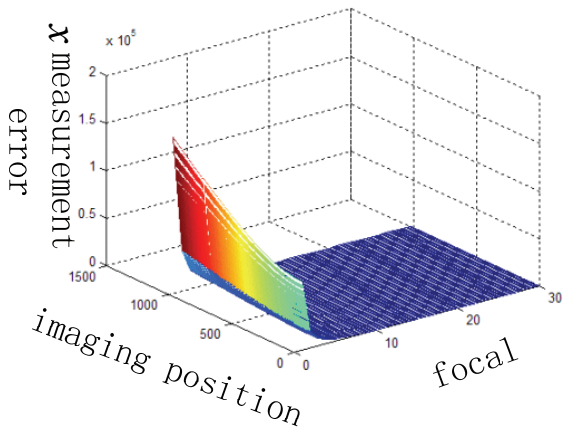
When the focal length is 10 mm, the baseline distance is 50 cm, the object distance ranges from 1 m to 5 m, then the x measurement error changes with the object distance and image position as shown in Fig. 3 (a), the y measurement error changes with the object distance and image position as shown in Fig. 3 (b), the z ranging error changes with the object distance as shown in Fig. 3 (c). It can be seen from Fig. 3, when the distance is more than 3.5 m, the error grows very quickly, in order to reduce the error, near distance is measured, but when the AUV speed is fast, larger field of view or far distance is needed in order to have enough overlap region. In order to take into account the speed of AUV, detection distance of 3 m is select.

When the focal length is 10 mm, the object distance is 3 m, the baseline distance variation range of 10 mm – 160 mm. Then the x measurement error changes with baseline distance and imaging position as shown in Fig. 4 (a), the y measurement error changes with baseline distance and the imaging position as shown in Fig. 4 (b), z ranging error changes with the baseline distance as shown in Fig. 4 (c). It can be seen from Fig. 4, when the focal length is less than 50 mm, the error growth very quickly, in order to reduce the error, longer baseline distance is needed. When the baseline distance is longer, the structure is more complex. In order to take into account the smart structure, baseline length of 50 mm is selected.

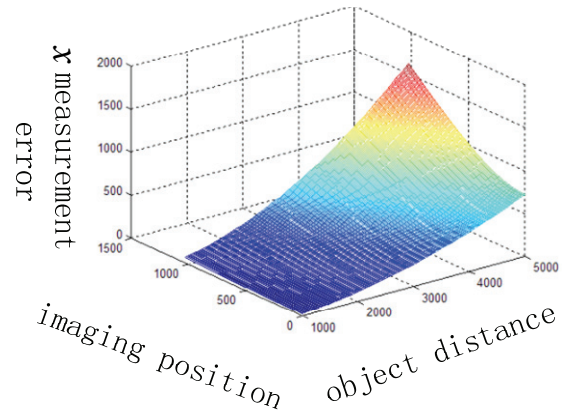
According to the optimization imaging structure of selected, the focal length is 10 mm, length is 3000 mm, the baseline length is 50 mm, the x measurement error changes with the imaging position

as shown in Fig. 5 (a), the y measurement error changes with the imaging position as shown in Fig. 5 (b). From formula (14) it is shown, that the z

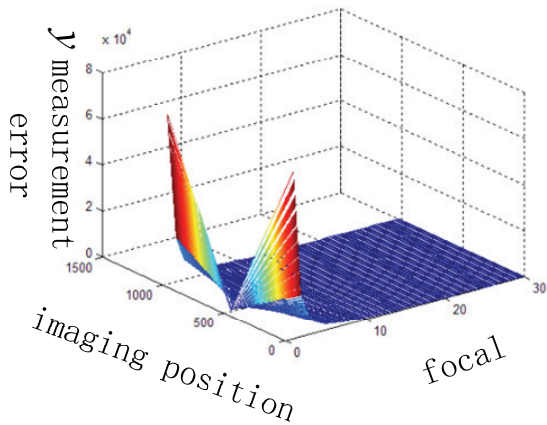
ranging error unchanged with the imaging position. So it can be seen in Fig. 5, the measurement noise variance is different with the imaging position.



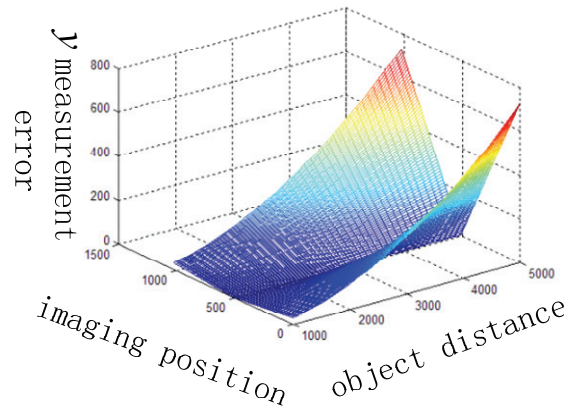
(a) X measurement error changes with focal length and image position.



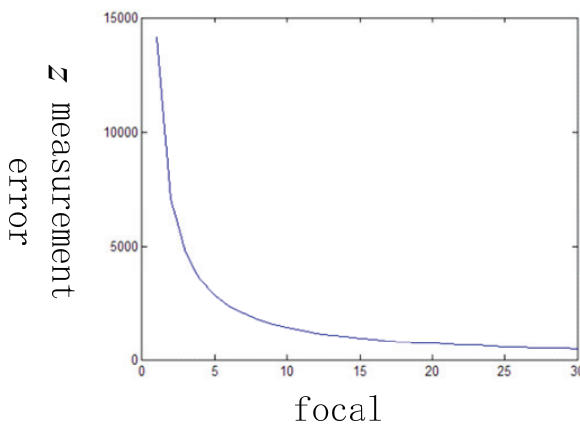
(a) X measurement error changes with the object distance and image position.



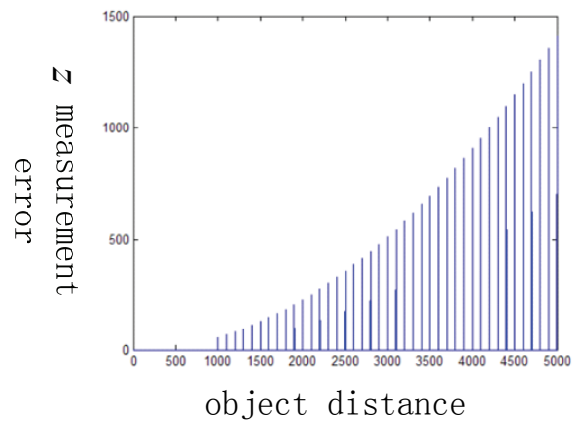
(b) y measurement error changes with focal length and image position.



(b) y measurement error changes with the object distance and image position.



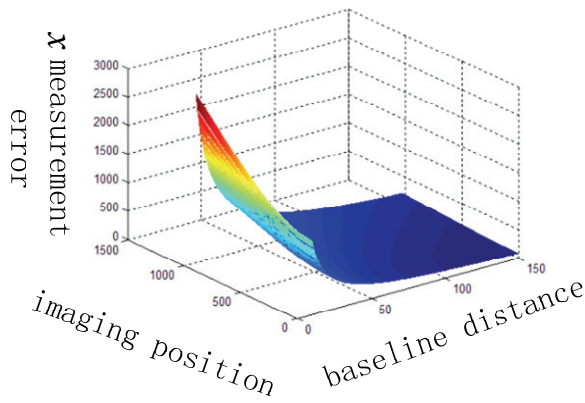
(c) Z ranging errors changes with the focal length.



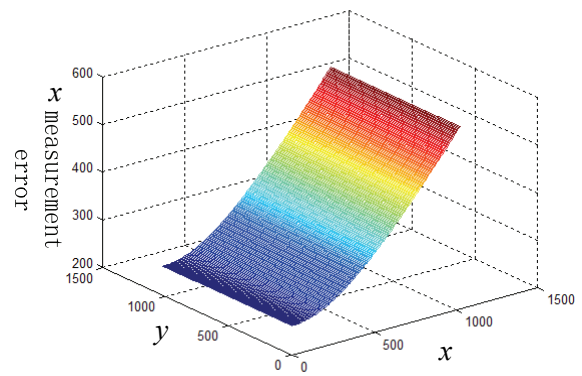
(c) Z ranging error changes with the object distance

Fig. 2. Measurement errors change with focal length and image position.

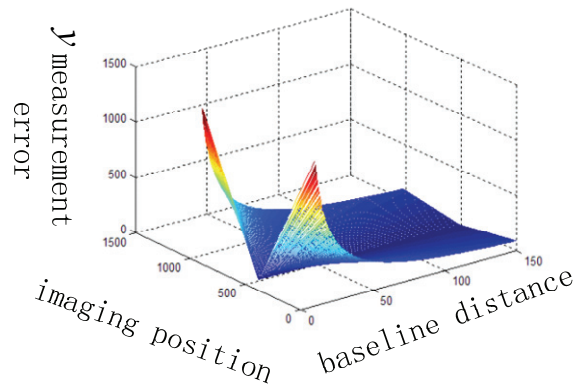
Fig. 3. Measurement error change with the object distance and image position.



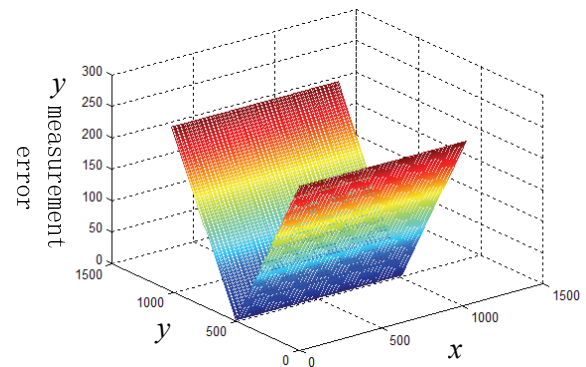
(a) X measurement error changes with baseline distance and imaging position.



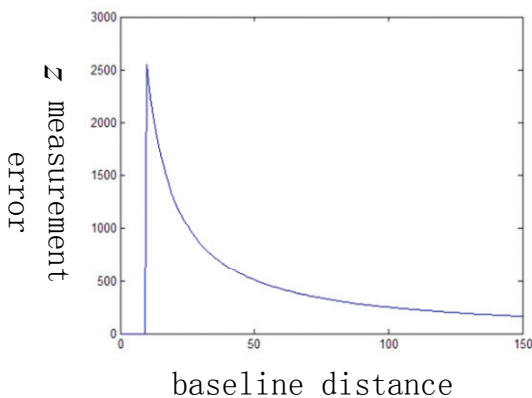
(a) X measurement error changes with the imaging position.



(b) y measurement error changes with baseline distance and imaging position.



(b) y measurement error changes with the imaging position.



(c) Z ranging error changes with the baseline distance.

Fig. 5. Measurement error changes with the imaging position.

Fig. 4. Measurement error change with baseline distance and imaging position.

3.2. Analysis of AUV 3D Motion Locating Accuracy

The optimized imaging structure can control the measurement error of space point to a certain extent, and the positioning accuracy of the AUV is controlled. But as shown in Fig. 5, measurement noise variance is different with imaging position, and least squares estimator in the formula (3) uses the

measured value with the same weight, doesn't consider the different, which results in that the AUV location estimation accuracy is not high. If the measured value is treated with the weighted method, the weight of precision high has larger weights, poor precision gets smaller, the weighted estimation of (3) equation is:

$$J(\hat{x}) = (m'_i - A_i \hat{x})^T W (m'_i - A_i \hat{x}) = \min, \quad (16)$$

where W is the type of positive definite weighting matrix with appropriate value. Here $W = R^{-1}$, the weighted least squares estimation is Markov estimation:

$$\hat{x} = \left(\sum_i A_i^T R^{-1} A_i \right)^{-1} \left(\sum_i A_i^T R^{-1} m'_i \right) \quad (17)$$

The mean square error:

$$E[\tilde{x}\tilde{x}^T] = (A^T R^{-1} A)^{-1} \quad (18)$$

The mean square error estimated as such is the minimum, and which is smaller than any other weighted least squares estimation, is the best estimation of the weighted least squares. For different space points measured value, it is used according to the different of precision, the estimation accuracy will be higher than the estimation precision with only high precision measuring value, which can effectively improve the AUV positioning accuracy finally.

4. Conclusion

In the AUV navigating and positioning based on the binocular vision, the measurement error of binocular vision is directly related to the AUV positioning accuracy. Based on the analysis of the measuring principle of binocular vision, the mathematical model is established to optimize the measurement accuracy, and is visualized analyzed with simulation graphics. The system structure and the imaging parameters of stereo vision system are optimized, which further verify the effectiveness of the mathematical model.

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