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Vision navigation algorithm for mine agent based on quaternion

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Abstract: Autonomous relative navigation is the key technology in mining or rescuing. On the basis of mine requirement and the theories of machine vision, an autonomous relative navigation algorithm for mine agent based on quaternion was proposed. In rotation transformation, this algorithm was represented by using quaternion. Because the Jacobi matrix of this method is lower than that of Hall algorithm, the calculation efficiency is improved by using this algorithm. The results of these experiments show that the computation burden of this algorithm based on quaternion is about half that of Hall algorithm. This algorithm based on quaternion is improved as a valid way to solve the problem of mine real-time navigation.

Key words: quaternion; mine agent; vision navigation

1 Introduction

There are two main ways to reduce the death number of mine accident. Using robot to explore or rescue at the first time is one way to improve the efficiency of mine succor. And the other one is to reduce the number of mine operators by using automation operation of mining. Therefore, as the key technology, relative navigation must be solved firstly.

So far, dead reckning, inertial navigation system (INS), beacons, map matching, radio frequency identification (RFID), Wi-Fi, vision navigation and the integration of above methods are some primary methods [1−3]. Dead reckoning is the simplest position estimator for mine equipment, in which the robot estimates its current position by step counting (integrating its combined steering and propulsion history) [4]. This method is vulnerable to bad calibration and provides only rough position estimation. Inertial navigation system is one of the most widely used dead-reckoning systems. They can provide continuous position, velocity and also orientation estimates, which are accurate for a short term subjected to drift due to noise of the sensor [5]. REID et al [6] employed inertial navigation techniques to accurately measure the three-dimensional (3D) path of the longwall shearer. Robot equipment can estimate its absolution position from known beacon locations, called beacons [7]. The disadvantages are that beacons must be emplaced within range, which means that the worksite of a robot equipment must be appropriately configured. To overcome the drawbacks of beacons, HANNU [8] built a navigation system for a load, haul and dump (LHD) truck. This navigation system was based on teaching the routes or route segments, recording the tunnel environment model while teaching and using laser scanners to correct the drift of dead reckoning positioning while driving in automatic mode. Map matching is a position way to analyze and estimate the position of the user from the matching results between real-time data and the known map data [9]. In order to get the known map of the complex environments, such as under mine, some new technologies were used. NUCHTER et al [10] provided a new solution to the simultaneous localization and mapping (SLAM) problem with six degrees of freedom for a mine. Radio frequency identification is a technology using radio waves to transfer data from an electronic tag, called RFID tag or label, attached to an object, through a reader for the purpose of identifying and tracking the object [11]. And

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JOHAN et al [12] developed a cheap and robust localization technique based on the deployment of inexpensive passive RFID tags at key points in the mine for the LHD vehicles. EVENNOU and MARX [13] have introduced a convenient way based on the use of the particle filter to reduce the effect of WiFi measurement noise and integrate more information such as the map of a building. Autonomous relative navigation based on machine vision might be a new research direction in the world currently, and is very suitable for autonomous mine navigation because it has many advantages, such as low-cost, high precision, autonomous ability and good practicality. Moreover, some researches about vision navigation have been studied recent years [14−15]. But these navigation algorithms having the drawbacks, such as low accuracy, complexity, inefficiency, must be improved. However, in rotation transformation, quaternion has the advantages, such as few parameters, fast calculation speed [16]. In this work, the navigation algorithm for mine agent based on quaternion was proposed. The algorithm model was introduced firstly thereinafter. And then correctness and validity of this algorithm was approved by using experiments.

2 Rotation transformation representation of 3D object by using quaternion

Quaternion is defined with $\boldsymbol{i}$, $\boldsymbol{j}$, $\boldsymbol{k}$ as its unit as follows,

$$\boldsymbol{Q}=(q_0,\boldsymbol{q})=q_0+q_1\boldsymbol{i}+q_2\boldsymbol{j}+q_3\boldsymbol{k} \tag{1}$$

where $\boldsymbol{i}$, $\boldsymbol{j}$ and $\boldsymbol{k}$ are basic elements of quaternion, and $\boldsymbol{i}^2=\boldsymbol{j}^2=\boldsymbol{k}^2=\boldsymbol{i}\cdot\boldsymbol{j}\cdot\boldsymbol{k}=-1$. Let $\boldsymbol{m}$ be a 3D vector, which is similar to quaternion definition, this 3D vector can be described as

$$\boldsymbol{Q}_{\mathrm{m}}=(0,\boldsymbol{m}) \tag{2}$$

Turn $\boldsymbol{m}$ into $\boldsymbol{m}'$ by using rotation transformation matrix $\boldsymbol{R}$. Similar to Eq. (2),

$$\boldsymbol{Q}_{\mathrm{m}'}=(0,\boldsymbol{m}') \tag{3}$$

Equation (1) can be described by using vector quaternion representation.

$$\boldsymbol{u}=\cos\frac{\theta}{2}+\boldsymbol{e}_n\sin\frac{\theta}{2} \tag{4}$$

Therefore, $\boldsymbol{m}$ can be represented by rotation transformation matrix $\boldsymbol{R}$ as

$$\boldsymbol{Q}_{\mathrm{m}'}=\boldsymbol{Q}\circ\boldsymbol{Q}_{\mathrm{m}}\circ\boldsymbol{Q}^{-1}=\boldsymbol{Q}\circ\boldsymbol{Q}_{\mathrm{m}}\circ\bar{\boldsymbol{Q}}=\boldsymbol{u}\boldsymbol{Q}_{\mathrm{m}}\boldsymbol{u}^{-1}=\boldsymbol{u}\boldsymbol{Q}_{\mathrm{m}}\bar{\boldsymbol{u}} \tag{5}$$

In Eq. (5), operator "$\circ$" stands for quaternion multiplication sign; $\boldsymbol{Q}^{-1}$ and $\boldsymbol{u}^{-1}$, $\bar{\boldsymbol{Q}}$ and $\bar{\boldsymbol{u}}$ are inverse, conjugate matrixes of $\boldsymbol{Q}$ and $\boldsymbol{u}$, respectively. Quaternion $\boldsymbol{Q}$ and $\boldsymbol{u}$ are consistent with transformation matrix $\boldsymbol{R}$. The relationship between $\boldsymbol{R}$ and $\boldsymbol{Q}$ can be deduced from Eq. (4).

$$\boldsymbol{m}'=(q_0-\boldsymbol{q}\cdot\boldsymbol{q})\boldsymbol{m}+2q_0(\boldsymbol{q}\times\boldsymbol{m})+2(\boldsymbol{q}\cdot\boldsymbol{m})\boldsymbol{q}=\boldsymbol{R}\boldsymbol{m} \tag{6}$$

3 Basis vision navigation algorithm

Usually, the main processes of vision navigation data collected by effective camera sensor are image data pretreatment, feature extraction, matching and space transformation. So, vision navigation algorithm basis is camera imaging technology. Camera imaging is a simple model from optics imaging. And the transformation from 3D to two-dimensional (2D) is represented by this model. Moreover the relationship of camera perspective projection is shown in Fig. 1.

In Fig. 1, o−ab stands for image pixels frame; o_i−x_iy_i stands for image physics frame; o_{C}−$x_{\mathrm{C}}y_{\mathrm{C}}z_{\mathrm{C}}$ stands for camera frame; o_{T}−$x_{\mathrm{T}}y_{\mathrm{T}}z_{\mathrm{T}}$ stands for object frame, which is consistent with body frame of mine agent.

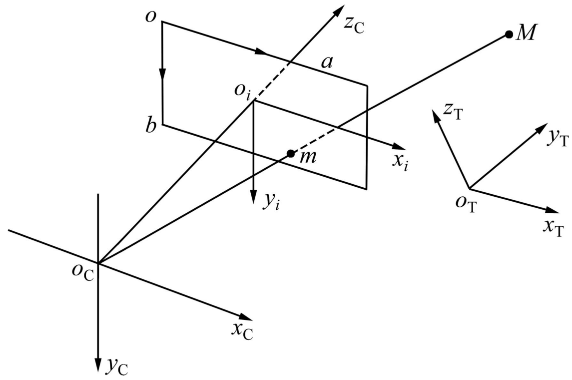

Fig. 1 Image frame, camera frame and object frame

According to Fig.1, the relationship between image physics frame and camera frame can be represented as

$$\begin{bmatrix} x_i \\ y_i \end{bmatrix}=f\begin{bmatrix} x_{\mathrm{C}}/z_{\mathrm{C}} \\ y_{\mathrm{C}}/z_{\mathrm{C}} \end{bmatrix} \tag{7}$$

where f is focal distance of camera.

Combining with homogeneous coordinate transformation, the relationship between object frame and camera frame can be described as

$$z_{\mathrm{C}}\begin{bmatrix} x_i \\ y_i \\ 1 \end{bmatrix}=\begin{bmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}\begin{bmatrix} \boldsymbol{R} & \boldsymbol{t} \\ \boldsymbol{0}^{\mathrm{T}} & 1 \end{bmatrix}\begin{bmatrix} x_{\mathrm{T}} \\ y_{\mathrm{T}} \\ z_{\mathrm{T}} \\ 1 \end{bmatrix}=$$

$$\boldsymbol{F}\begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} x_{\mathrm{T}} \\ y_{\mathrm{T}} \\ z_{\mathrm{T}} \\ 1 \end{bmatrix} \tag{8}$$

where t_i (i=1, 2, 3) stand for translation parameters; $r_{i,k}$ (i=1, 2, 3; k=1, 2, 3) stand for rotation transformation parameters.

The basic equation of vision navigation can be deduced from Eq. (8).

$$\begin{bmatrix} x_i \\ y_i \\ 1 \end{bmatrix} = \frac{1}{z_C}\boldsymbol{F}\begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} x_T \\ y_T \\ z_T \\ 1 \end{bmatrix} \tag{9}$$

4 Vision navigation algorithm based on quaternion

In coordinating transformation problems, there are one scale modulus and six other independency parameters, that is, three rotation parameters and three translation parameters. From Eq. (9), it can be seen that $r_{i,k}$ (i=1,2,3; k=1,2,3) and t_i (i=1,2,3) are all taken as unknown parameters in Hall algorithm. Thus, there are twelve unknown parameters. When the number n of observation points satisfies $n\geq 6$, Eq. (9) can be calculated. In order to reduce the number of unknown parameters, rotation transformation will be solved by using quaternion representation. Combining with Eq. (9), let

$$\begin{aligned} X_S &= r_{11}x_T + r_{12}y_T + r_{13}z_T + t_1 = \\ &(q_0^2 + q_1^2 - q_2^2 - q_3^2)x_T + 2(q_1q_2 + q_0q_3)y_T + \\ &2(q_3q_1 - q_0q_2)z_T + t_1 \end{aligned} \tag{10}$$

$$\begin{aligned} Y_S &= r_{21}x_T + r_{22}y_T + r_{23}z_T + t_2 = \\ &2(q_1q_2 - q_0q_3)x_T + (q_0^2 - q_1^2 + q_2^2 - q_3^2)y_T + \\ &2(q_2q_3 + q_0q_1)z_T + t_2 \end{aligned} \tag{11}$$

$$\begin{aligned} Z_S &= r_{31}x_T + r_{32}y_T + r_{33}z_T + t_3 = \\ &2(q_3q_1 + q_0q_2)x_T + 2(q_2q_3 - q_0q_1)y_T + \\ &(q_0^2 - q_1^2 - q_2^2 + q_3^2)z_T + t_3 \end{aligned} \tag{12}$$

Thus, Eq. (9) can be described as

$$\begin{bmatrix} x_i \\ y_i \\ 1 \end{bmatrix} = \frac{1}{z_C}\boldsymbol{F}\begin{bmatrix} X_S \\ Y_S \\ Z_S \\ 1 \end{bmatrix} \tag{13}$$

Through simple transformation of Eq. (13), Eq. (14) is obtained as

$$\begin{bmatrix} x_i \\ y_i \end{bmatrix} = f\begin{bmatrix} X_S / Z_S \\ Y_S / Z_S \end{bmatrix} \tag{14}$$

Obviously, Eq. (14) is a nonlinearization function. In order to calculate by computer program, Eq. (14) must be linearized, and described by Taylor series as

$$\begin{bmatrix} x_i \\ y_i \end{bmatrix} = \begin{bmatrix} x_0 + \Delta x \\ y_0 + \Delta y \end{bmatrix} \tag{15}$$

where x_0 and y_0 can be calculated from Eq. (14).

$$\begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} = \begin{bmatrix} \dfrac{\partial x}{\partial q_0}\Delta q_0 + \dfrac{\partial x}{\partial \boldsymbol{q}}\Delta \boldsymbol{q} + \dfrac{\partial x}{\partial \boldsymbol{t}}\Delta \boldsymbol{t} \\ \dfrac{\partial y}{\partial q_0}\Delta q_0 + \dfrac{\partial y}{\partial \boldsymbol{q}}\Delta \boldsymbol{q} + \dfrac{\partial y}{\partial \boldsymbol{t}}\Delta \boldsymbol{t} \end{bmatrix} \tag{16}$$

In Eq. (16), $\Delta\boldsymbol{q}=(\Delta q_1, \Delta q_2, \Delta q_3)^T$; $\Delta\boldsymbol{t}=(\Delta t_1, \Delta t_2, \Delta t_3)^T$.

According to theory, the processing above needs to iteratively calculate until corrected value less than defined threshold value. If the number of observation points more than four, the least-squares solutions can be processed by using indirect adjustment model.

5 Experiments and analyses

5.1 Introduction of experiment instruments

Vision instrument of mine agent is Canon Digital IXUS V3 CCD camera. The effective pixels number of this camera is 320 million, and the maximum pixels number is 2048×1538, 2X optical zoom, 3.2X digital zoom, that is, effective focal length is 35 mm. And its lens size is 35−70 mm. Mine object is made up of two cuboid modules. Moreover twelve feature markers are made on this object. And then this object is fixed on the machine vision page table entry (PTE) developed by Microvision Digital Image Technology Co.,Ltd. The object movement can be controlled by the machine vision PTE, as shown in Fig. 2.

Fig. 2 Vision intelligent console system

In addition, experiment instruments include a tripod, a steel measuring tape and another data processing computer, which configuration parameters are HP Pavilion Intel (R), Pentium (R) 4, CPU 3.06 GHz, 512 MB, except for the machine vision PTE computer. The post processing results are given according to this processing computer.

5.2 Experiment results

1) Object frame definition and object feature points measurement. As shown in Fig. 3, select the joint of the center interfaces of big cuboid module and small cuboid module as origin of coordinates, that is, a vector parallel to feature points 4 and 5 as x_T axis; a vector parallel to feature point 12 and point 13 as y_T axis; z_T meets right-hand rule, even plummet. The coordinates of feature cross center are measured, as listed in Table 1.

Fig. 3 Feature and frame of object

Table 1 Feature point coordinates

Feature point	x_T/m	y_T/m	z_T/m
1	−0.036	−0.164	−0.044
2	0.0300	−0.167	−0.044
3	0.0000	−0.087	−0.044
4	−0.1595	0.009	−0.1435
5	0.1525	0.009	−0.1435
6	−0.1595	0.099	−0.1435
7	0.1535	0.1000	−0.1435
8	0.004	0.058	−0.1435
9	0.044	−0.1670	−0.0350
10	0.044	−0.1685	0.0260
11	0.044	0.0870	0
12	0.1665	0.008	−0.1355
13	0.1665	0.008	0.1265
14	0.1675	0.099	−0.1355
15	0.1675	0.097	0.1255
16	0.1670	0.052	0.0015

2) Extract feature from the collection of image data by using mathematical morphology algorithm. Feature points are matched and their pixel coordinates are gotten using the software HALCON 7.1 made by Germanic MVTec Co. Finally, the pixel coordinates are transformed into image physics coordinates using our own program.

3) Relative attitude and position parameters between camera and object are calculated by the algorithm based on quaternion. Let initial parameters of quaternion be $\boldsymbol{q}$=[1 0 0 0]^T, and translation parameters be $\boldsymbol{t}$=[0 0 0.976]^T. When the precision threshold value less than 10^{-3}, root mean square error m_0 meets 10^{-4} level, as shown in Fig. 4. The calculation results of relative attitude and position parameters are show in Figs. 5 and 6. And the results of algorithms based-on quaternion or Hall algorithm are shown in Figs. 4 to 6. The data processing time of the algorithm based on quaternion and Hall algorithm are 30 ms and 78 ms, respectively.

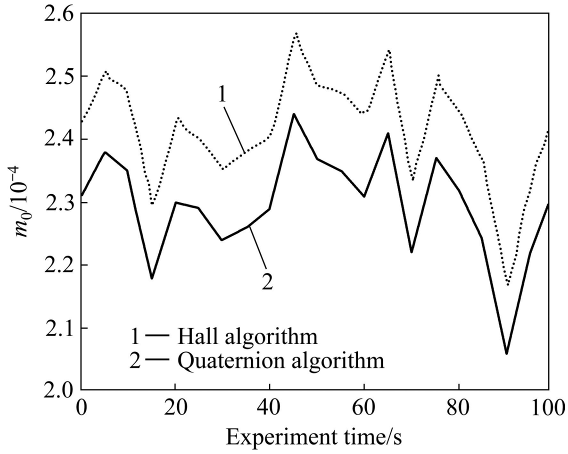

Fig. 4 Value of m_0 of algorithm based-on quaternion and Hall algorithm

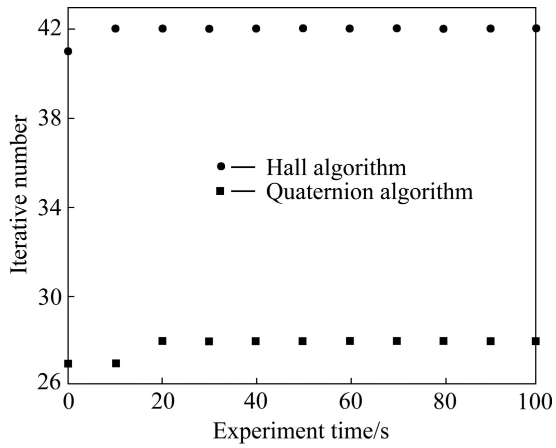

Fig. 5 Iterative number of algorithm based-on quaternion and Hall algorithm

5.3 Experiment analyses

From the experiment results above, it can be seen that equivalence precision of the algorithms based-on quaternion and Hall algorithm can be met, that is, root mean square error m_0 meets 10^{-4} level, when the threshold value of translation parameters meets 10^{-3} level.

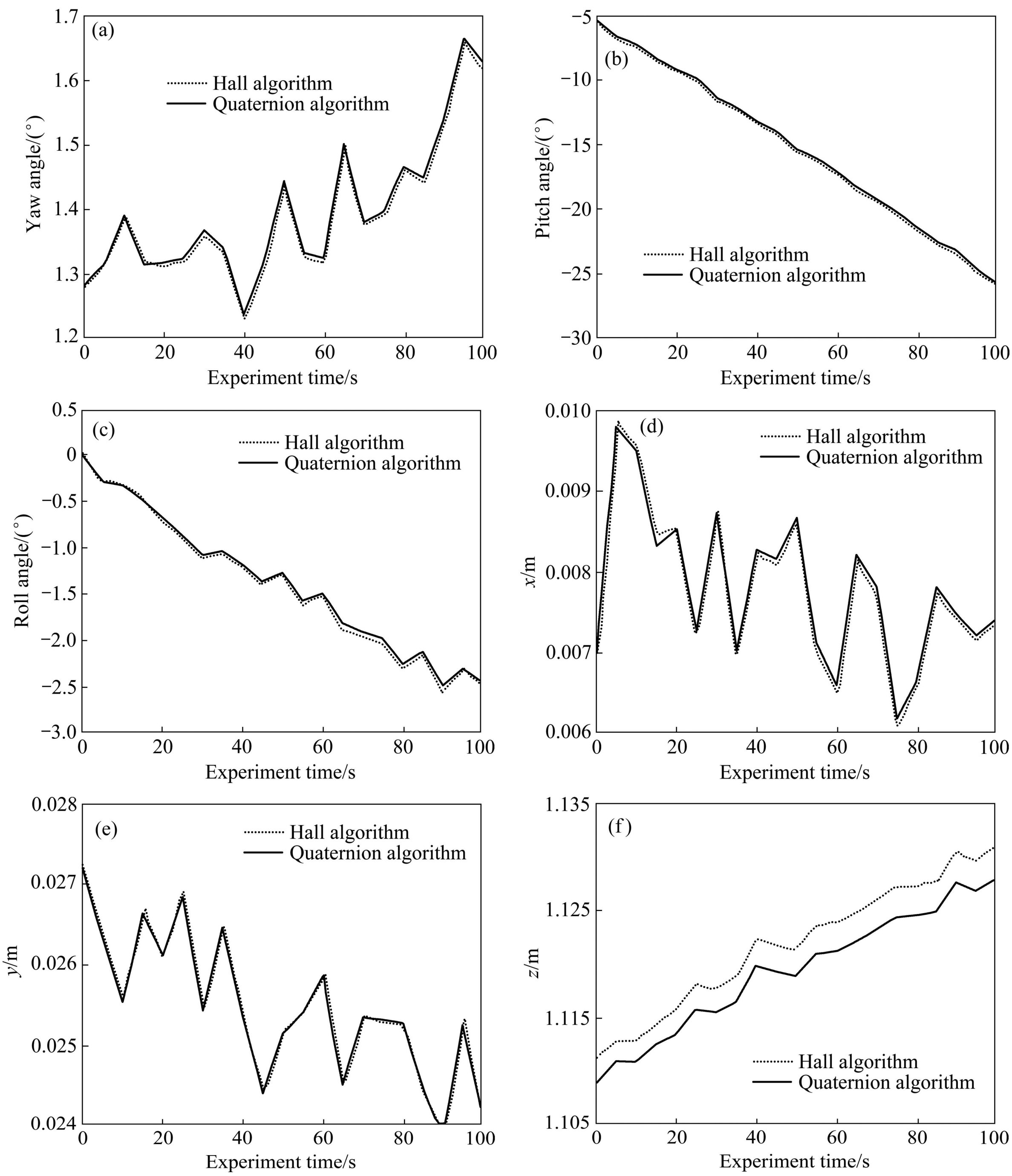

Fig. 6 Relative navigation results of the algorithm based-on quaternion or Hall algorithm: (a) Relative yaw angle; (b) Relative pitch angle; (c) Relative roll angle; (d) Relative coordinates of x axis; (e) Relative coordinates of y axis; (f) Relative coordinates of z axis

Moreover, the precision of the algorithms based-on quaternion is better than that of Hall algorithm slightly. From Fig. 5, the calculation iterative number of algorithm based-on Hall is about double of the algorithm based on quaternion. Therefore, the calculation speed of the algorithm based on quaternion is increased by about two times compared with that of Hall algorithm because the number of rotation representation parameters of quaternion are seven, while those of Hall algorithm are twelve. So, the Jacobi matrix of quaternion method is lower. The calculation efficiency is improved.

6 Conclusions

1) A relative navigation algorithm based on quaternion for mine agent is proposed. An experiment to test the quaternion algorithm better than Hall algorithm is carried out. Results show that under the equivalence precision conditions, the calculation efficiency of the quaternion method is improved by two times compared

with Hall algorithm.

2) For the off-line or post processing method taken in the experiment, the real-time relative attitude and position parameters should be estimated in future work by building state equation based on quaternion combine with mine characters and applications.

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