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Improved SINS anti-disturbance coarse alignment algorithm

CHENG Yan[1], QIN Yong-yuan[1], MEI Chun-bo[1]

Abstract. Several realizations of anti-disturbance coarse alignment algorithm are compared in SINS inertial system. Combined with the filtering performance of data pre-processing error characteristic of TRIAD attitude determination algorithm and particularity of alignment in inertial frame, the principle is put forward for optimization of algorithm. Furthermore, the advantages of Request attitude determination algorithm in coarse alignment are discussed, the selection principle of optimal weight and forgetting factor are also presented. Optimization Principles are verified for rationality by simulation and the result shows that the coarse alignment based on Request algorithm has higher accuracy and converges more rapidly.

Key words. Coarse alignment, data pre-preprocessing, TRIAD Request,Optimization Principles.

1. Introduction

Strapdown inertial anti-disturbance coarse alignment needs to solve two aspects of the interference problem, one is the interference of the angular motion; the second is the interference of the linear acceleration. By introducing the auxiliary inertial system [1], the angular motion disturbance can be completely isolated and no longer pose a threat to alignment. According to the characteristic of the useful signal and the interference signal in the frequency domain, the classical digital filtering scheme is introduced into the alignment algorithm as a data preprocessing link to achieve the suppression of line acceleration interference.

The analysis of the roughing alignment algorithm, mainly focuses on the selection of the data prepurpose scheme [2 ~ 4] and the error analysis [5,6] of the attitude determination algorithm, and the two are independent of each other. In fact, there is some correlation between the filter characteristic of the pre-filter and the concrete realization of the attitude-forming algorithm. According to this, and considering the particularity of the alignment, it is possible to further discuss the optimization

[1] Workshop 1 - Department of Automation Control, Northweatern Ploytechnial University, XI'an 710072, China

and improvement of the rough alignment algorithm. This is little discussion. In this paper, we will attempt to analyze the optimization principle and improvement method of the anti - jamming rough alignment algorithm by synthetically analyzing all aspects of rough alignment and combining with the actual alignment background.

2. Coordinate System Definition and Inertia Coarse Alignment Algorithm

(1) Geocentric earth coordinate systeme The origin is located in the center of the earth, the axis z_{e}along the direction of the Earth's rotation; axis x_{e}in the equatorial plane, from the center of the heart to the beginning of the meridian; axis $y_{\mathrm{e}}$and axisx_{e}, axis z_{e}constitute the right hand coordinate system.

(2) Navigation coordinate systemn: take the local geographical coordinate system, the origin is located in the carrier center of gravity, the axis x_{n}pointing to the east; axis y_{n}pointing north;axisz_{n} pointing sky.

(3)Navigation inertiasystemi$_{\mathrm{n}}$: Inertial coordinate system, and coincides with the navigation system at the beginning of the rough alignment.

(4)Body coordinate systemb: the origin is located in the carrier center of gravity, the axisx_{b} y_{b} z_{b} respectively, along the carrier axis to the right, along the vertical axis forward, along the vertical axis.

(5)Body inertial systemi$_{\mathrm{b}}$: it is an inertial coordinate system, and it overlaps with the load system of the beginning moment of the coarse alignment.

After the introduction of the navigation inertial system i$_{\mathrm{n}}$and the body inertial systemi$_{\mathrm{b}}$, the solution of the time-varying stitching quaternion $q_{\mathrm{n}}^{\mathrm{b}}$(t)under the disturbance base condition can be described by the following figure, as shown in Fig1.

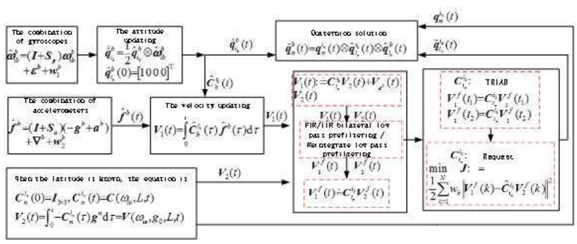

Fig. 1. schematic diagram of inertial alignment algorithm

The analytical expressions and related algorithms involved in figure 1 can be described as follows:

1. Matrix $C_{\mathrm{n}}^{\mathrm{i_n}}$(t)and V_2(t)

$$C_{\mathrm{n}}^{\mathrm{i_n}}(\mathrm{t}) = \begin{bmatrix} \cos(\omega_{\mathrm{ie}}\mathrm{t}) & -\sin\mathrm{L}\sin(\omega_{\mathrm{ie}}\mathrm{t}) & \cos\mathrm{L}\sin(\omega_{\mathrm{ie}}\mathrm{t}) \\ \sin\mathrm{L}\sin(\omega_{\mathrm{ie}}\mathrm{t}) & \sin^2\mathrm{L}\cos(\omega_{\mathrm{ie}}\mathrm{t}) + \cos^2\mathrm{L} & \sin\mathrm{L}\cos\mathrm{L}\,(1-\cos(\omega_{\mathrm{ie}}\mathrm{t})) \\ -\cos\mathrm{L}\sin(\omega_{\mathrm{ie}}\mathrm{t}) & \sin\mathrm{L}\cos\mathrm{L}\,(1-\cos(\omega_{\mathrm{ie}}\mathrm{t})) & \cos^2\mathrm{L}\cos(\omega_{\mathrm{ie}}\mathrm{t}) + \sin^2\mathrm{L} \end{bmatrix} \tag{1}$$

$$V_2(\mathrm{t}) = \frac{\mathrm{g}_0}{\omega_{\mathrm{ie}}}\begin{bmatrix} -\cos\mathrm{L}\cos(\omega_{\mathrm{ie}}\mathrm{t}) \\ \sin\mathrm{L}\cos\mathrm{L}(\omega_{\mathrm{ie}}\mathrm{t}-\sin(\omega_{\mathrm{ie}}\mathrm{t})) \\ \cos^2\mathrm{L}\sin(\omega_{\mathrm{ie}}\mathrm{t})+\omega_{\mathrm{ie}}\mathrm{t}\sin^2\mathrm{L}\end{bmatrix} \tag{2}$$

(2)TRIAD

Select two different times of velocity integral vector and the attitude matrix is to be constructed

$$C_{\mathrm{i_n}}^{\mathrm{i_b}} = \begin{bmatrix} \left(V_1^{\mathrm{f}}(\mathrm{t}_2)\right)^{\mathrm{T}} \\ \left(V_1^{\mathrm{f}}(\mathrm{t}_2)\times V_1^{\mathrm{f}}(\mathrm{t}_1)\right)^{\mathrm{T}} \\ \left[V_1^{\mathrm{f}}(\mathrm{t}_2)\times\left(V_1^{\mathrm{f}}(\mathrm{t}_2)\times V_1^{\mathrm{f}}(\mathrm{t}_1)\right)\right]^{\mathrm{T}}\end{bmatrix}^{-1} \bullet \begin{bmatrix} \left(V_2^{\mathrm{f}}(\mathrm{t}_2)\right)^{\mathrm{T}} \\ \left(V_2^{\mathrm{f}}(\mathrm{t}_2)\times V_2^{\mathrm{f}}(\mathrm{t}_1)\right)^{\mathrm{T}} \\ \left[V_2^{\mathrm{f}}(\mathrm{t}_2)\times\left(V_2^{\mathrm{f}}(\mathrm{t}_2)\times V_2^{\mathrm{f}}(\mathrm{t}_1)\right)\right]^{\mathrm{T}}\end{bmatrix} \tag{3}$$

(3)Request [7]

As shown in figure 1, the Request algorithm USES the velocity integral vector at all times to minimize the following cost function.

$$\min_{\hat{C}_{\mathrm{i_n}}^{\mathrm{i_b}}\in SO(3)} J = \frac{1}{2}\sum_{\mathrm{k}=1}^{\mathrm{N}}\mathrm{w_k}\left\|V_1^{\mathrm{f}}(\mathrm{t_k})-\hat{C}_{\mathrm{i_n}}^{\mathrm{i_b}}V_2^{\mathrm{f}}(\mathrm{t_k})\right\|^2 \tag{4}$$

Its recursive method can be described as:

Initialization

$$K_0 = \mathbf{0}_{4\times4}, \quad \mathrm{m}_0 = 0 \tag{5}$$

When new integrals resutlspeoduced, matrix Kupdates,

$$\begin{gathered} v_1^{\mathrm{f}}(\mathrm{t_k}) = V_1^{\mathrm{f}}(\mathrm{t_k})/\left\|V_1^{\mathrm{f}}(\mathrm{t_k})\right\|, \quad v_2^{\mathrm{f}}(\mathrm{t_k}) = V_2^{\mathrm{f}}(\mathrm{t_k})/\left\|V_2^{\mathrm{f}}(\mathrm{t_k})\right\| \\ \delta\sigma = \alpha_{\mathrm{k}}\left(v_2^{\mathrm{f}}(\mathrm{t_k})\right)^{\mathrm{T}}v_1^{\mathrm{f}}(\mathrm{t_k}), \quad \delta B = \alpha_{\mathrm{k}}\ v_2^{\mathrm{f}}(\mathrm{t_k})\left(v_1^{\mathrm{f}}(\mathrm{t_k})\right)^{\mathrm{T}} \\ \delta z = \alpha_{\mathrm{k}}v_2^{\mathrm{f}}(\mathrm{t_k})\times v_1^{\mathrm{f}}(\mathrm{t_k}), \quad \delta S = \delta B + \delta B^{\mathrm{T}} \\ \mathrm{m_k} = \mathrm{m_{k-1}} + \alpha_{\mathrm{k}}, \quad K_{\mathrm{k}} = \beta\frac{\mathrm{m_{k-1}}}{\mathrm{m_k}}K_{\mathrm{k-1}} + \frac{1}{\mathrm{m_k}}\begin{bmatrix}\delta S-\delta\sigma I & \delta z \\ \delta z^{\mathrm{T}} & \delta\sigma\end{bmatrix}\end{gathered} \tag{6}$$

The quaternions $q_{\mathrm{i_n}}^{\mathrm{i_b}}$are solved according to the current matrix$K$

$$\begin{gathered} K = \begin{bmatrix} S-\sigma I & z \\ z^{\mathrm{T}} & \sigma\end{bmatrix}, \qquad Kq_{\mathrm{i_n}}^{\mathrm{i_b}} = \lambda_{\max}q_{\mathrm{i_n}}^{\mathrm{i_b}} \\ y = \left[(\lambda_{\max}+\sigma)I-S\right]^{-1}z, \quad q_{\mathrm{i_n}}^{\mathrm{i_b}} = \frac{1}{\sqrt{1+|y|^2}}\begin{bmatrix}1 \\ y\end{bmatrix}\end{gathered} \tag{7}$$

3. Several different implementation schemes for coarse alignment and their comparison

The traditional anti-sloshing indirect resolution is based on the TRIAD algorithm [1~ 6], and different data preprocessing schemes are used. In this paper, comparing different data preprocessing scheme are centered in filter, such as performance index under the condition of a given filter, compare different filter order of high and low, and the size of the amount of calculation, and stable time length, etc[2].

Starting from on purpose, just stay on comparisons of filter is not enough, the following will combine the filtering features of filter, the error of the TRIAD algorithm characteristics and the actual background, to the basic principles of TRIAD algorithm are given.

(1)error characteristics of TRIAD algorithm

Based on the basic vector($V_1^{\mathrm{f}}(\mathrm{t}_1)$, $V_2^{\mathrm{f}}(\mathrm{t}_1)$) , ($V_1^{\mathrm{f}}(\mathrm{t}_2)$, $V_2^{\mathrm{f}}(\mathrm{t}_2)$), there are three kinds of factors affecting the accuracy of TRIAD: first, the accuracy of the vector $V_{\mathrm{i}}^{\mathrm{f}}(\mathrm{t_k})$, $\mathrm{i},\mathrm{k}=1,2$; Second, the Angle of the Angle between the vector $V_1^{\mathrm{f}}(\mathrm{t}_1)$and $V_1^{\mathrm{f}}(\mathrm{t}_2)$; Thirdly, three vector pairs of TRIAD algorithm are completed, and if the accuracy of the time vector $\mathrm{t}_2$is higher, the TRIAD algorithm described is the highest resolution [8].

(2)Filter filter characteristics

Integral to inertial system inside than force as the object of data preprocessing, the original interference acceleration has been an integral operation, so the analysis filter characteristics, need analysis of the integral process and subsequent mutual effect of the selected filter scheme.

First, the effect of integral operation on the accuracy of useful signal

Under the condition of the perturbation base, the disturbance acceleration is a periodic signal, and the device error is ignored,

$$\overline{\xi_{\mathrm{D}}}(x_{\mathrm{D}},y_{\mathrm{D}})=\sum_{i=1}^{\mathrm{M}}\sum_{j=1}^{\mathrm{2N}}\overline{\xi_{\mathrm{D}i,j}}(x_{\mathrm{D}},y_{\mathrm{D}}) \tag{8}$$

In the disturbance condition, the periodic interference $(V_a(\mathrm{t})-V_a(0))$of the amplitude is limited, and the useful signal$V_{1\mathrm{g}}(\mathrm{t})$ integral increases with increasingt. Therefore, integral operation is equivalent to improve the accuracy of useful signal

Secondly, the effect of FIR/IIR/mean low-pass filter on the accuracy of useful signal

In the case of FIR filter, when the filter is stable, the signal accuracy of the filtered signal is consistent. In the case of IIR and mean filtering, the more data that is involved in filtering, the stronger the suppression effect is, which is that the accuracy of the filtered signal is higher and higher.

(3)the particularity of alignment under inertial system

In the inertial system, the vector which participate in the TRIAD, its direction changes in inertial space is extremely slow. If the interval of the selected attitude vector is shorter, the angle between the vectors will be very small, so that the TRIAD algorithm will be the residual interference is very sensitive.

In summary, two basic principles of optimizing the TRIAD algorithm can be obtained:

First, the principle of certainty. One of them, the fixed position vector, should select the filtering result of the current moment, and the TRIAD should be implemented in a formula (3)description.

Second, the principle of uncertainty. Another board vector need to weigh the choice of the following two factors: the lower TRIAD algorithm for filtering the perspective of residual error sensitivity, should choose to stay away from the current moment of filtering results, to maximize the two vector Angle. Based on the availability of high accuracy, the filtering results should be close to the current moment.

The above two principles have some guiding significance, but because of the existence of the second principle, making the optimization TRIAD algorithm is not operational.

Diagram 1 is also presented with a different kind of a set of form algorithm, which is the Request algorithm, which USES all available data in the optimal weighted method, which is more operable and more efficient than the TRIAD algorithm.

4. Optimization of Request algorithm

In the Request algorithm described in Equations (4) to (7), the weighting factor α_{k} and the forgetting factorβ need to be set in advance and will directly affect the estimation result, and the setting of both need according to the position vector of relative accuracy and its variation law with time. Based on the analysis of the filter characteristics in the last section, the precision of the position vector$V_1^{\mathrm{f}}(\mathrm{t})$ is increasing over time t.

In particular,the integral transformation, IIR filter, mean filter on the positioning of the vector accuracy can be approximated as the degree of time is proportional to the time. Therefore, if IIR filtering is used to process the integral transformation result, the weighting factor and the forgetting factor can be set as follows

$$\alpha_{\mathrm{k}} \propto \mathrm{k}^2, \quad \beta \in [\ 0.9, \quad 1\ ) \tag{9}$$

There is no quantitative criterion for the choice of forgetting factor β. If the value is small, the forgetting speed is too fast, which will lead to the algorithm relying too much on the current filtering result, which is more sensitive to the current time filtering residual error of the current moment. If the value is larger, the overall alignment of the convergence rate will be slowed by the influence of the previous filtering results, although the weighted value α_{k} is reduced.

5. Simulation verification

This section is mainly used to simulate the basic conclusions in the second and third sections.

Simulation of ship mooring condition. Under the action of wind and wave, the ship's pitchθ, roll Angle γ and azimuth Angle ψ do periodical changes:

$\theta = 8^\circ \cos(2\pi/6 + \pi/4)$ $\gamma = 12^\circ \cos(2\pi/12 + \pi/7)$$\psi = 30^\circ + 5^\circ \cos(2\pi/8 + \pi/3)$

The line acceleration caused by the vertical swing, the vertical oscillation and the transverse oscillation is,

$$\mathrm{v_{Di}} = \mathrm{A_{Di}}\omega_{\mathrm{Di}} \cos(\omega_{\mathrm{Di}}\mathrm{t}+\phi_{\mathrm{Di}}), \qquad \mathrm{i} = \mathrm{x, y, z}$$

Among them,

$A_{Dx} = 0.02m$,$A_{Dy} = 0.03m$,$A_{Dz} = 0.3m$,$\omega_{Di} = 2\pi/T_{Di}$,and$T_{Dx} = 4s$,$T_{Dy} = 5s$,$T_{Dz} = 6s$;$\phi_{Dx} = \pi/4$,$\phi_{Dy} = \pi/5$,$\phi_{Dz} = \pi/7$.

Set for gyro random constant drift 0.01°/h, the random walk coefficient for0.001°/h; the zero bais of the accelerometer for$4 \times 10^{-5}g_0$, and the standard deviation of the white noise is$1 \times 10^{-5}g_0 \cdot \sqrt{s}$. The error of the calibration coefficient is 20 PPM.

The cut-off frequency of the FIR/IIR filter is 0.02 Hz, the initial frequency of the resistance band is 0.1 Hz, and the band ripple is 0.01 db, and the resistance band attenuation is 60 db.

Using these parameters to get the same set of trajectory simulation, to verify the following two contents:

First, the validity of the two basic principles of the optimization TRIAD algorithm.

Second, the comparison between the Request algorithm and the TRIAD algorithm, and the influence of the forgetting factor on the Request algorithm.

The selection of two position vectors in TRIAD algorithm is shown in table 1.

Table 1. Selection of three different position vectors in TRIAD

Vector Selection	$V_1^f(t_1)/V_2^f(t_1)$	$V_1^f(t_2)/V_2^f(t_2)$
Scheme 1	$V_1^f(t_1) := V_1^f(t_k - 1)$, $V_2^f(t_2) := V_2^f(t_k - 1)$	$V_1^f(t_2) := V_1^f(t_k)$, $V_2^f(t_2) := V_2^f(t_k)$
Scheme 2	$V_1^f(t_1) := V_1^f(t_k - 10)$, $V_2^f(t_2) := V_2^f(t_k - 10)$	$V_1^f(t_2) := V_1^f(t_k)$, $V_2^f(t_2) := V_2^f(t_k)$
Scheme 3	$V_1^f(t_1) := V_1^f(t_k - 20)$, $V_2^f(t_2) := V_2^f(t_k - 20)$	$V_1^f(t_2) := V_1^f(t_k)$, $V_2^f(t_2) := V_2^f(t_k)$

In the Request algorithm, the weight coefficient$\alpha_k = k^2$ and the forgetting factor were respectively 0.9, 0.99 and 0.995.

Because the horizontal Angle error converges very fast, contrast is not obvious, the azimuth error Angle of convergence is given only, as shown in figure 2 ˜ figure 5 .

The alignment results of the horizontal and vertical comparisons of 2˜ 4 can be obtained as follows:

(1)The filtering effect of mean filtering is not as good as FIR/IIR filter, and the residual error is larger and the alignment error is larger. The FIR/IIR filtering effect is equivalent to the result of alignment, but the IIR calculation is much smaller than FIR.

(2)As shown in figure 2, when the filtering effect is poor and the residual interference is large, priority should be given to increase the fixed position vector theory Angle.

(3) Comparing figure 2 and figure 4, we can see that when the filter effect is better, the residual error is small, the priority should be given to improve the accuracy of the fixed position vector.

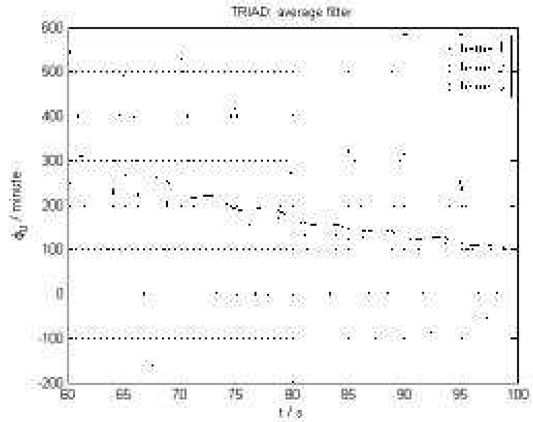

Fig. 2. Mean filtering +TRIAD azimuth error alignment result

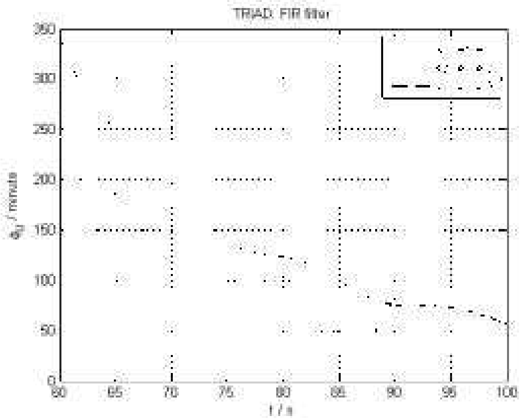

Fig. 3. FIR filter +TRIAD azimuth error alignment result

The three alignment results are consistent with the two principles of optimizing the TRIAD algorithm presented in the second section.

Furthermore, compared with Fig. 4 and Fig. 5, the convergence rate and alignment accuracy of the Request algorithm are better than the TRIAD algorithm under the same conditions.

Secondly, compared with the three curves in FIG. 5, it can be seen that when the forgetting factor is larger, the algorithm converges rapidly and the amplitude of the result amplitude fluctuates greatly. The forgetting factor is less, the convergence speed is slow and the result is stable.

The selection of the forgetting factor is related to the overall accuracy of the filter, and if the filter has a lower overall accuracy, then the forgetting factor should be as large as possible; conversely, the forgetting factor can be taken smaller.

From the practical point of view, the overall accuracy level of the filtered data can be divided into three levels, high precision, the forgetting factor can be taken as

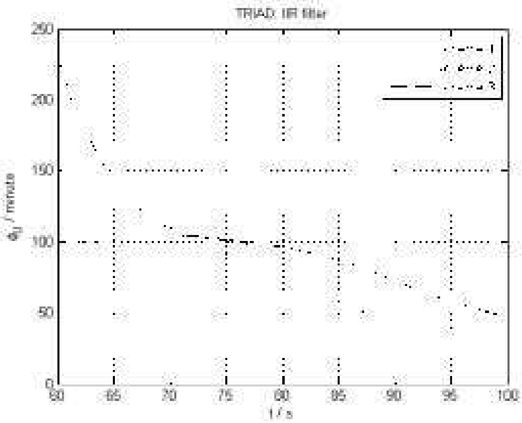

Fig. 4. IIR filter +TRIADazimuth error alignment result

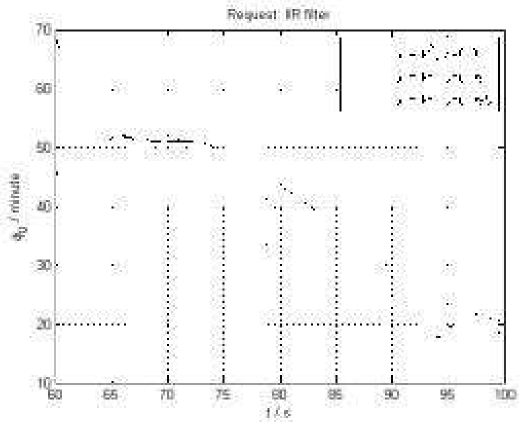

Fig. 5. IIRfilter+Requestazimuth error alignment result

0.99; precision medium, the forgetting factor can be taken as 0.999; low precision, the forgetting factor can be set to 1.

6. Summary

In this paper, two kinds of indirect resolution coarse alignment schemes based on TRIAD and Request determination algorithm are discussed. Based on the characteristics of the data preprocessing, the two algorithms have the error characteristics and the special background of alignment, and the basic optimization principles are proposed for the two algorithms. The simulation analysis shows that the proposed optimization principle is reasonable and effective. The horizontal comparison also shows that the alignment accuracy and convergence speed of the alignment scheme based on Request algorithm are superior to the alignment scheme based on TRIAD.

References

[1] Qin. Yongyuan,Yan . ongmin,GuDongqing: *A Clever Way of SINS Coarse Alignment despite Roching Ship.*Journal of Northwestern Polytechnical University*23* (2005), No. 5, 681–684.

[2] Yan, Gongmin,Bai. Liang, Weng. Jun: *SINS Anti-Rocking Disturbance Initial Alignment Based on Frequency Domain Isolation Operator.*Journal of Astromsutics *32* (2011), No. 7, 1486–1490.

[3] Zhao. Changshan,Qin. Yongyuan, Wei. Liang: *A Gravity-Based Anti-Ineterence Coarse Alignment Algorithm.*Journal of Astromsutics*31* (2010), No. 10,2335–2339.

[4] Lian. Junxiang,Tang. Yonggang,Wu. Meiping: *Study on SINS Alignment Algorithm with Inertial Frame for Swaying Bases.* Journal of National University of Defense Technology *29* (2007), No. 5, 93–97.

[5] Peter. M. G: *Coarse alignment of a ship's strapdown inertial attitude reference system using velocity loci.*IEEE Transactions on Instrumentation and Measurement *60* (2011), No. 6, 1930–1941.

[6] Qin. Yongyuan, Mei. Chunbo, Bai. Liang: *Error and calculation problem analysis of coase alignment method with inertial frame for SINS.* Journal of Chinese Inertial Technology*18* (2010),No. 6, 648–652.

[7] O. Rasheed, Bello, A. Robert: *Multi-stage Hydraulically Fractured Horizontal Shale Gas Well Rate Transient Analysis.* The North Africa Technical Conference and Exhibition, 14-17 February, 2010.

[8] Jiang. Y. F: *Error analysis of analytic coarse alignment.*IEEE Transactions on Aerospace and Eletronic Systems *34* (1998), No. 1, 334–337.

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