Extraction of Disturbance Signals Based on the Inertial Sensor with a Blind Source Separation Method

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Abstract: The inertial sensor is a key component in the photoelectric tracking system mounted on the moving platform, and its disturbance information extraction is a prerequisite for decoupling the system disturbance. In this paper, to get the specific signal of \( f_s \) Hz, firstly, source signal of \( 2 \times f_s \) Hz from the inertial sensor is needed. Then, single channel signal with frequency \( 2 \times f_s \) is constructed into 2 aliased signals with the frequency of \( f_s \) by down-sampling. Finally, a BSS (Blind Source Separation, BSS) algorithm is used to extract the disturbance signal in the aliased signals. Simulation results of ship borne data show that the algorithm can accurately extract the high-frequency disturbance signal of about 33 Hz in the aliased signals. The experimental results of the platform prove that the spectrum of the disturbance signal (10 Hz) and the spectrum of the target signal (0.1 Hz) do not overlap each other, and the correlation coefficient between the perturbation signal and the perturbation source signal is as high as 0.9976, which means the extraction of disturbance signal in the inertial sensor signals is realized.

1. Introduction

On the optoelectronic tracking system based on the motion platform, the motion of the target and the interference of the external environment will be coupled to the tracking platform and introduce the jitter in LOS (line-of-sight), which causes the LOS to deviate from the tracking target and lead to the declining of the tracking performance. Therefore, the inertial stabilization platform is usually used to suppress the disturbance of the system to ensure the stability of the LOS[1]. It is well known that if we can extract the disturbance signal from the target motion information and the disturbance mixed signal, this will help to greatly reduce the interference with feedforward methods. This effect is not achieved by feedback suppression methods.

To extract the disturbance signal from the inertial sensor, some filter methods are commonly adopted. Since the target is far from the tracking platform, its motion state at an angle is mainly distributed in the low frequency. By filtering the low frequency target signal in the aliased signals, the difference between the filtered signal and the original aliased signals is used to obtain the perturbation signal in the aliased signals. The commonly filtering methods are: IIR filtering[2], wavelet filtering[3] and Kalman filtering[4]. These methods are effective, but they have too many artificial parameters in the filtering process. Moreover, the prior knowledge of the signal is strict and the filtering process is...
complex, which is not conducive to engineering implementation. BSS (Blind Source Separation) refers to a method which extracts each source signal using only observation signals. Compared to commonly methods BSS needs not prior knowledge of source signals and transmission channel characteristics. Therefore, BSS is suitable for inertial sensor signals processing of optoelectronic tracking system.

In this paper, the inertial sensor aliasing signal of 2 times the sampling frequency (2×f_s) is obtained according to the sampling frequency (f_s) required for actual engineering. Then, single channel signal with frequency 2×f_s is constructed into 2 aliased signals with the frequency of f_s by down-sampling. Finally, the BSS is used to extract the disturbance signal in the aliased signals. The algorithm can transform single channel signal to multichannel signal without adding additional sensors. Compared with the traditional filtering methods, the algorithm can extract the high frequency interference signal in the inertial sensor aliasing signals without the artificial filter parameters. It avoids the dependence of the prior knowledge on the signal and the error caused by the artificial experience setting in the filtering process. The algorithm is simple and convenient for engineering application and is of the great adaptability.

2. Down-sampling and blind source separation

2.1. Down-sampling

Due to the limitation of conditions and costs, only one sensor is placed on the tracking rack in a direction of the photoelectric tracking system. Separating the disturbance signal from the multichannel aliasing signals acquired by a single sensor is an extreme case of under-determined blind source separation. In practical applications, it is necessary to process a single sensor signal to construct a multichannel observation signal and convert the under-determined blind source separation into a positive blind source separation. Down-sampling is the process of compressing a plurality of observed data points with high sampling frequencies into data points of low sampling frequency[5]. In this paper, the down-sampling method is used to deal with the single inertial sensor signal and obtain two dual channel signals with 1/2 sampling rate.

Sampling data is taken from M points (M is an integer). The sampling factor is M, which means that the sampled data compressed by M times. Under the condition of practical engineering, if the sampling frequency of the inertial sensor signal is f_s, the inertial signal x(n) with a sampling frequency of M×f_s should be obtained. Down-sampling equation is shown as equation (1):

\[
\begin{align*}
    y_1(n) &= \sum_{k=0}^{N} h(k)x(nM - k) \\
    y_2(n) &= \sum_{k=0}^{N} h(k)x([nM - 1] - k)
\end{align*}
\]

(1)

Where y_1(n), y_2(n) are two sensor signals with frequency f_s obtained by down-sampling the signal x(n), n = 1,2,…, N/M, N is the number of data points for the signal x(n), h(k) is the impulse response of the system when the input is δ[n]. The Nyquist frequency is M×f_s/2 before sampling. after down sampling, the Nyquist frequency is f_s/2. When the maximum frequency component of the 2 signals is lower than f_s/2 after the signal is down sampled, the desired 2 inertial sensor signals with a sampling frequency of f_s can be obtained, the conversion of a single channel signal to dual channel signals is realized.

2.2. Blind source separation

Blind source separation[6] can be represented by a matrix as in equation (2):

\[
X = AS
\]

(2)

Where S is the unknown n source signals, A is the mixing matrix m×n, and X is the
m observation signals received by the sensor. In general, the dimension of the source signal and the observed signal is the same, that is, \( A \) is the full rank matrix (\( A^{-1}A = I \)). The goal of blind source separation is to find the inverse matrix estimation \( \hat{W} = A^{-1} \) of \( A \), so as to obtain the estimated value \( \hat{S} \) of the source signals as equation (3):

\[
\hat{S} = Y = WX = A^{-1} \quad \text{AS} = S
\]  

(3)

The two signals with the frequency \( f_s \) obtained by down-sampling are the observation signals. After blind source separation of the observed signals, the interference signals in the aliased signals are extracted. The perturbation signal and target signal received by the tracking frame on the optoelectronic motion platform are independent, and the disturbance signal is a complex non-Gaussian signal. Therefore, the blind source separation algorithm adopted in this paper is a FastICA algorithm based on the maximum negative entropy[7].

From the information theory, it is known that the Gauss variable has the maximum negative entropy in all the random variables of the equal variance. The negative entropy is a modified form of entropy, so the negative entropy can be used to measure the non-Gauss property. The negative entropy of the random variable \( Y \) is defined as equation (4):

\[
N_g(Y) = H(Y_{Gauss}) - H(Y)
\]  

(4)

Where \( Y_{Gauss} \) is a Gaussian random variable with the same variance as \( Y \), \( H(\cdot) \) is the differential entropy of the random variable, and \( N_g(\cdot) \) is the negative entropy sought. The larger value of \( N_g(Y) \) means \( Y \) has the smaller differential entropy and stronger non-Gaussian. Using the negative entropy definition to solve the problem requires the probability density distribution function of \( Y \) is known, but it is practically impossible. Therefore, the following approximate equation (5) is used:

\[
N_g(Y) = \{E[g(Y)] - E[g(Y_{Gauss})]\}^2
\]  

(5)

Where \( E[\cdot] \) is the mean operation. \( g(\cdot) \) is a non-linear function whose value is given by equation (6):

\[
\begin{align*}
g_1(y) &= \tanh(a_1y) \\
g_2(y) &= y \times \exp(-y^2/2) \\
g_3(y) &= y^3
\end{align*}
\]  

(6)

Where \( 1 \leq a_1 \leq 2 \), \( a_1 = 1 \) is taken. FastICA algorithm is a fast optimization iterative algorithm with a batch method, iteration is involved in the operation by a large number of sample data. The FastICA rule is to find a direction so that \( W^T \) has the greatest non-Gaussian. Firstly, the algorithm whitens the data and then obtains \( E\{W^T Y\} \parallel W \parallel = 1 \). The approximate iterative formula of the FastICA algorithm by the Newton iteration method is shown as equation(7):

\[
\begin{align*}
W^* &= E\{X g(W^T X)\} - E\{g(W^T X)\} W \\
W &= W^\top / ||W^\top||
\end{align*}
\]  

(7)

Where \( W^\top \) is the new value of \( W \). The two inertial sensor signals obtained by down-sampling are used as observation signals. The separation matrix \( W \) is estimated by FastICA algorithm, and then the target signal and disturbance signal in the motion platform stability system are recovered. Finally the disturbance information is extracted. The specific process of blind source separation after down-sampling the inertial sensor signal is shown in Figure 1:
3. Process of disturbance signal extraction algorithm

Traditional filtering methods for extracting disturbance information, such as IIR filtering, wavelet filtering and Kalman filtering, require too much signal priori knowledge and artificial settings. The IIR filtering method needs to know the specific frequency of the signal in advance and artificially design the pass-band of the filter. The wavelet filtering method needs to artificially select the threshold function and the wavelet basis function, and the Kalman filter needs to artificially establish an accurate mathematical model of the disturbance signal. Because of the complexity of the output signal of inertial sensor in photoelectric systems, the inaccuracy of parameters or model settings will lead to inaccurate extraction of disturbance information.

In order to solve the problem of artificially setting in traditional methods, this algorithm uses a combination of down-sampling and blind source separation to provide an adaptive and rapid implementation of motion without relying on signal prior knowledge and human experience settings. The method of extracting disturbance information from the inertial sensor signals in the platform photoelectric tracking system is shown in Figure 2.

Specific steps are as follows:
1) Determine the sampling frequency $f_s$ of the inertial sensor signal required for the optical tracking system of the motion platform in the actual project.
2) Acquire an inertial sensor signal with a sampling frequency of $2 \times f_s$ .
3) Down-sample the inertial sensor signal, the sampling factor is 2, the sampling period is 2 times of the original, and two aliased signals with a frequency of $f_s$ are obtained.
4) Perform spectrum analysis on the two aliased signals obtained by down-sampling to determine whether all of the most frequent components of the signal are lower than $f_s / 2$ . If the condition is not satisfied, the inertial sensor signal is reacquired, If the condition is satisfied , proceed to the next step.
5) The two signals obtained by down-sampling are observed signals, and signal separation is performed using FastICA algorithm.
6) The target signal and the disturbance signal are analyzed by spectrum analysis, and the disturbance signal in the 2 signals is selected.

4. Simulation analysis

In the marine environment, waves always exist and affect the movement of the ship, causing the ship to be in a swaying state almost at all times. Therefore, the working environment of the inertial sensor
in the ship-borne environment is complicated. Due to the high precision and easy installation of the gyro, the inertial sensor used in Ship-borne optical tracking system is generally optical fibre gyro(FOG)[8]. FOG will simultaneously detect the angular velocity of the interference caused by the waves and the own vibration of ship and the angular velocity caused by the target of the system tracking.[9]. The technical problem is to extract the disturbance signal of the onboard optoelectronic system detected by FOG other than the angular velocity caused by the target motion. In order to verify the algorithm, this paper simulates the actual data output by an inertial sensor in the photoelectric tracking system under actual ship-borne conditions with MATLAB. The FOG signal sampling frequency required in practical engineering is 100 Hz, and the FOG output aliasing signal sampled at 200 Hz frequency is shown in Figure 3.

![Figure 3. FOG signal with a frequency of 200 Hz.](image)

Next, sample the FOG signal with a frequency of 200 Hz, sampling factor $m = 2$. Then it obtains 2 aliasing signals with a frequency of $f_s/2$ (100Hz), as shown in Figure 4. Figure 4(a) is a time domain diagram of two signals, and Figure 4(b) is a spectrum diagram corresponding to the signal in Figure 4(a).

![Figure 4. Two FOG signals with a sampling frequency of 100 Hz.](image)

Figure 4 shows that the FOG’s signals in the ship-borne background are mainly composed of low-frequency target angular velocity signals around 0.01Hz and high-frequency disturbance signals around 33Hz, and the maximum frequency components are below $f_s/2$, satisfying the Nyquist theorem and proceeding to the next step.

Taking the two aliased signals with frequency of 100 Hz in Figure 4 as observation signals, the target angular velocity signal and disturbance signal in the aliased signals are separated using FastICA algorithm, as shown in Figure 5(a). The separation signal 1 is the target angular velocity signal, while the separation signal 2 is the disturbance signal. The spectrum analysis is performed on the target angular velocity signal and the interference signal in Figure 5(a), and the result is shown in Figure 5(b).
It can be seen from Figure 5(b) that the low-frequency target signal of about 0.01 Hz and the frequency spectrum of the high-frequency segment disturbance signal of about 33 Hz obtained by the algorithm are not mixed with each other. Finally, the separation signal 2 in Figure 5(a) is extracted, that is, the disturbance information of high frequency rate segment about 33 Hz in the FOG output aliasing signals of the ship-borne photoelectric tracking system can be realized.

5. Experimental results and discussion

5.1. Correlation coefficient
For the degree of similarity between the source perturbation signal and the perturbation signal extracted from the inertial sensor signal by this algorithm, this paper analyzes the spectrum diagram of the signal and calculates it with the correlation coefficient $\rho$, as shown in equation (8).

$$
\rho_{XY} = \frac{\sum_{i=1}^{N} (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{N} (X_i - \bar{X})^2} \sqrt{\sum_{i=1}^{N} (Y_i - \bar{Y})^2}}
$$

Where $X$ and $Y$ are the source signal and the corresponding extracted signal, $N$ is the number of signal sampling points, and $0 \leq |\rho_{XY}| \leq 1$ when $|\rho_{XY}| > 0.8$ the degree of similarity is high. When the two signals are the same, the correlation coefficient is 1[10]. When the degree of spectrum aliasing of the disturbance signal extracted from the aliased signal is lower and the correlation coefficient is higher, the disturbance signal extraction is more accurate.

5.2. Experimental results and analysis
This paper uses the one-dimensional stable platform shown in Figure 6 to simulate the ship's photoelectric tracking system. The system is consisted of two single-axis turrets. Below is the disturbance table, which is used to provide the disturbance angular velocity. The above is the stable platform. The fiber optic gyro is mounted on the stable platform. The disturbance table and the stable platform are directly driven by the respective torque motors.

![Figure 6. One-dimensional stability platform.](image-url)
XW-FG70-20 fiber optic gyroscope is used in the system. The sampling frequency of the output signal of the gyroscope is 500Hz. The target source signal and the disturbance source signal obtained by the experiment are shown in Figure 7. Among them, Figure 7(a) shows the signal output from the fiber optic gyro and its spectrum when the target turbulence signal with a frequency of 0.1Hz is added to the stable platform. The signal in the frequency band above 10Hz is the noise of the fiber gyro. Figure 7(b) is a disturbance signal with frequency 1Hz and its spectrum diagram for a disturbed platform.

![Figure 7](https://example.com/figure7.png)

**Figure 7.** Target source signal and disturbance source signal.

The stabilized platform and disturbance turntable work simultaneously, the sampling frequency is 1000Hz, and the FOG signal output aliasing signal is shown in Figure 8(a). By down-sampling the signal, two signals with a sampling frequency of 500Hz are obtained, and their time-domain and spectrum are shown in Figure 8(b).

![Figure 8](https://example.com/figure8.png)

**Figure 8.** FOG signal and its down-sampled signal.

The two sampling frequencies obtained by down-sampling are 500Hz, and the blind source separation based on the FastICA algorithm is performed for the two observed signals. Finally, the separated target signal and the disturbance signal are analyzed by spectrum, and the disturbance signal is extracted. Most of the traditional disturbance information extraction methods use signal filtering methods. The literature [3] proposes to wavelet filter the low frequency target signal in the aliased signals, and then makes the difference between the filtered signal and the original alias signals to obtain the perturbation signal in the alias signals. In this paper, we choose db8 wavelet base, 6 layers of decomposition layers and soft threshold function to experiment on the method proposed in the literature [3]. The experimental results of the method proposed by the literature [3] and the algorithm of this paper are shown in Figure 9. Figure 9(a) shows the disturbance signal and its spectrum extracted by the method proposed in the literature [3], and Figure 9(b) shows the disturbance signal and its spectrum extracted by the algorithm.
The correlation coefficients of the disturbance signals extracted from the literature [3] method and this algorithm are calculated respectively with the disturbance source signals shown in Figure 7 (b), and the results are shown in Table 1.

Table 1. Comparison of correlation coefficients.

|                  | Literature [3] method | Algorithm in this paper |
|------------------|-----------------------|-------------------------|
| Correlation coefficient | 0.7423                | 0.9976                  |

Comparing the spectrum of the perturbation signal obtained by the method of document [3] and the algorithm of this paper in Figure 9, the 1 Hz disturbance signal extracted by the method [3] is mixed with the 0.1 Hz target signal and 10 Hz noise signal, and the aliasing phenomenon is serious. However, the frequency of the 1Hz disturbance signal extracted by this algorithm does not contain other frequency signals, and there is no aliasing phenomenon. Comparing the correlation coefficients in Table 1, it is found that the correlation coefficient obtained by the literature [3] method is 0.7423, and the correlation coefficient obtained by the algorithm is 0.9976 which is much larger than the literature [3] method. That is, compared with the literature [3] method, the frequency spectrum aliasing of the perturbation signal extracted by this algorithm is lower, the correlation coefficient of the perturbation source signal is higher, and the accuracy of signal extraction result is higher.

In addition, the use of wavelet filtering in the literature [3] to process signal requires signal prior knowledge and human experience to set different wavelet bases, decomposition layers, and threshold functions for the 0.1 Hz target signal and the 10 Hz noise signal, respectively. Improper manual setting can cause large errors in the filtering results. In this algorithm, the disturbance signals in the alias signal of inertial sensors can be extracted without human setting, which avoids the dependence of the prior knowledge on the signal and the error caused by artificial experience in the filtering process.

6. Conclusion
In this paper, a method of extracting the disturbance signal from the inertial sensor signals in the photoelectric system based on motion platform is constructed with the method of down-sampling and blind source separation. The MATLAB simulation of the measured data under the carrier background is carried out. The results show that the algorithm can accurately extract the disturbance signal of the FOG signal on the tracking frame. In order to verify the practicability of this algorithm in engineering, this paper sets up a photoelectric system to track the one-dimensional stable platform to simulate the real ship-borne photoelectric system. Comparing the experimental results of the algorithm with the experimental results of the wavelet filtering method proposed in the literature [3], it is found that the frequency spectrum aliasing of the disturbance signal extracted by the algorithm is lower, and the correlation coefficient of the disturbance source signal is higher, which means the signal extraction result is more accurate. It provides a solid foundation for achieving high-precision beam-axis stability control for optoelectronic tracking systems on motion platforms. The next step is to optimize the algorithm and get a method that can accurately extract the disturbance signals of various frequency bands.
References
[1] Xia Y 2013 Research on inertial stability control technology in sports platform (Chengdu: University of Chinese Academy of Sciences)
[2] Qiang-Wen F U and Zhang Y M 2005 Journal of Transclution Technology Practical method in signal processing of fog 18(1) pp 101-104
[3] Daubechies I 1990 Journal of Renewable & Sustainable Energy The wavelet transform, time-frequency localization and signal analysis 36(5) pp 961-1005
[4] Lu Y H 2016 Measurement & Control Technology Research on Gyro Noise Reduction Technology Based on Kalman Filter 35(9) pp 40-42
[5] Gu D F, Zhao X F and Yi D Y 2010 Data Acquisition and Processing Downsampling method for GPS dual-frequency satellite observation data 25(1) pp 98-101
[6] Ye Y, Zhang Z L, Zeng J and Et A L 2008 Applied Mathematics & Computation A fast and adaptive ICA algorithm with its application to fetal electrocardiogram extraction 205(2) pp 799-806
[7] Li F Q, Zheng B Z and Jia S H 2011 Henan Science Extraction of ECG signals based on negative entropy maximization of fastica 29(12) pp 1509-1512
[8] Gaiffe T 2002 Optical Fiber Sensors Conference Tech-nical Digest From R&D brassboards to navigation grade FOG-based INS: the experience of Photonetics Of 2002. IEEE 2002 p 1-4 vol.1
[9] Zhao G L, Yang Q H and Li S 2014 Journal of Liaoning Technical University The effect of fiber optic gyro calibration error on ship Strapdown Inertial Navigation System 33(12) pp 1635-1639
[10] Han J H and Chen J B A 2004 Journal of Beijing Institute of Technology Study on the Rapid Transfer Alignment in Marine Environment 24(10) pp 894-865