Time-delay error compensation for POS based on PSO tuning SVM

Bin Gu1*, Jianli Li1, Zhaoxing Lu1 and Jiancheng Fang1

1 School of Instrumentation and Optoelectronic Engineering, Beihang University, Beijing, Beijing, 100191, China

*Corresponding author’s e-mail: oucgubin@163.com

Abstract. Position and orientation system (POS) is widely applied in remote sensing applications, which provide high-accuracy position, velocity, and attitude information for remote sensing motion compensation. As a multisensory system, time-delay usually occurs during signal preprocessing, transmission, integration, filtering, etc., which decrease the measurement accuracy. As the POS motion parameter varies nonlinearly, the time-delay error can’t be precisely compensated by the conventional linear method. To solve this problem, a novel time-delay error compensation method based on Support Vector Machine (SVM) is proposed, and Particle Swarm Optimization (PSO) is used to optimize the key parameters of SVM. In verifying the proposed method, a flight experiment was conducted. Experimental results show that the proposed method can effectively compensate the time-delay error of POS, and is more accurate than the conventional one.

1. Introduction

The Position and Orientation System (POS), is a Inertial Navigation System (INS)/Global Navigation Satellite System (GNSS) integrated measurement equipment, which provides high-accuracy space-time reference for airborne earth observation system to compensate the motion deviation’s effect on sensing imagery[1-3]. It consists of Inertial Measurement Unit (IMU), POS Computer System (PCS), carrier phase differential GNSS and post-processing software[4]. As a multisensory system, there exist time-delays in POS during signal preprocessing, integration, filtering, etc. IMU commonly uses filter method to suppress random noise and improve the signal to noise ratio. However, the mechanical dither will become an adverse disturbance vibration to imaging payloads[5], and will result in a measurement instability and strapdown algorithm error of POS. So the dither noise must be suppressed by filter. Infinite impulse response filter and finite impulse response filter are commonly used in engineering for noise suppression[6], both of which will inevitably lead to time-delay.

POS is a high-precise space-time reference used in airborne earth observation system. Time-delay will undoubtedly decrease the measuring accuracy. In real time application, time-delays will affect the control of inertial stabilization platform and the imaging accuracy of sensors. In post-processing application, time-delays make the POS fail to get the motion parameters at the right time for imaging, which further introduce errors for information fusion and motion error compensation. What’s more, the bad effects are more serious under high dynamic conditions. Several studies of time-delay error compensation methods have been undertaken. An optimized multi-degree uncoupled antivibration system was designed for dithered RLG POS[7], and the time-delay caused by the digital low pass filter is calculated and compensated by post-processing. But this method cannot deal with the time delay error in real time application. A linear interpolation method was used to deal with the time delay errors
among multi-sensors[8]. However, POS doesn’t move along a straight line or do uniform or uniformly accelerated motion, and the kinematic parameters of the POS are non-linear and time-varying. Therefore, the compensation accuracy of conventional linear method is relatively low.

In order to further improve the compensation accuracy, a time-delay error compensation method based on Particle Swarm Optimization (PSO) tuning support vector machine (SVM) is proposed in this paper. Different schemes of training data have been determined for real-time compensation and post-processing compensation. To improve the compensation accuracy and generalization ability, the model parameters are optimized by PSO. Experimental results show that this method can effectively reduce the time-delay error, thereby improve the measurement accuracy of POS.

2. Time-Delay Error Compensation Principle for POS

POS can continuously provide an optimized position, velocity, and attitude solution. These motion parameters vary differently under different conditions: The position, velocity and dynamic scenario of POS change significantly during acceleration and deceleration, the attitude changes rapidly during turning. However, the POS motion parameters change relatively slow within a short time, and can be described by modelling.

The time-delay of POS $\Delta t$ can be calculated or measured precisely. The POS outputs motion parameter $X_i$ at time $t_i + \Delta t$, and the real time of $X_i$ is $t_i$, $X_i = [L_i, \lambda_i, h_i, v_i^E, v_i^N, v_i^U, \phi_i, \theta_i, \gamma_i]$ represents the latitude, longitude, altitude, east velocity, north velocity, upward velocity, heading angle, pitch angle and roll angle at time $t_i$, respectively. Then, $X_{k+2}, X_{k+1}, X_k, X_{k-1}, X_{k-2}......$ are the POS motion parameters at real time $t_{k+2}, t_{k+1}, t_k, t_{k-1}, t_{k-2}(real\text{\hspace{1mm}time\hspace{1mm}means\hspace{1mm}the\hspace{1mm}exact\hspace{1mm}moment\hspace{1mm}without\hspace{1mm}time-delay)$ The POS output period is $T$. The timing relationship of POS output information is shown in Figure 1.

![Figure 1. Timing relationship of POS output information.](image)

Based on the true motion parameters of POS $X_{k+2}, X_{k+1}, X_k, X_{k-1}, X_{k-2}......$ and output period $T$, the motion parameter of POS $X(t)$ during $[t_{k+2}, t_{k+1}, t_k, t_{k-1}, t_{k-2}]$ can be modeled ($\Delta t' > 0$), and further the true output of POS $X_{k+\Delta}$ can be calculated.

The time-delay error compensation model for POS can be expressed as:

$$X_{k+\Delta} = F_k(Z_k)$$

$$Z_k = [X_{k}, X_{k+1}, \cdots, X_{k-N}, \Delta t]$$

where $X_{k+\Delta}$ is the motion parameter of POS at time $t_k + \Delta t$, $F_k(\cdot)$ is the optimized objective function at time $t_k + \Delta t$, $X_{k+i} = [L_{k+i}, \lambda_{k+i}, h_{k+i}, v_{k+i}^E, v_{k+i}^N, v_{k+i}^U, \phi_{k+i}, \theta_{k+i}, \gamma_{k+i}]$ is the position, velocity, and attitude solution at time $t_{k+i}, i = 0,1,\cdots,N$. Besides, in real-time application, appropriate $N$ need to be chosen in order to meet the real-time requirement $\Delta t_p < T$ in real-time application, $\Delta t_p$ is the computation time of $X_{k+\Delta}$.
3. Time-delay Error Compensation Method Based on PSO Tuning SVM

In order to fit the time-delay error shown as Eqs. (1), the training data of the model need to be determined first. For real-time compensation, only the motion parameters before the output time $t_i + \Delta t$ can be used as the training data, and the training data for model $F_i(\cdot)$ can be expressed as:

$$A_i = \left[ \tilde{Z}_{i,1}, X_{k_i-S_i+1} \right] \left[ \tilde{Z}_{i,1}^{*}, X_{k_i-S_i+2} \right] \cdots \left[ \tilde{Z}_{i,1}^{*}, X_{k_i-S_i+1} \right] \cdots \left[ \tilde{Z}_{i,j}, X_{k_i-S_i+j} \right] \left[ \tilde{Z}_{i,j}^{*}, X_{k_i-S_i+j} \right]$$

\(i = 0, 1, \cdots, S-1, \ j = 0, 1, \cdots, S \ & \ i + j \leq S, \) \(i + j \leq S, \) \(j = 0, 1, \cdots, S \) and \(i + j \leq S, \) the volume of training data is $M_p = S(S+1)/2$.

For post-processing compensation, all of the motion parameters can be used as the training data, and the training data for model $F_i(\cdot)$ can be expressed as:

$$A_{ip} = \left[ \left[ \tilde{Z}_{i,1}, X_{k_i-S_i+1} \right] \left[ \tilde{Z}_{i,1}^{*}, X_{k_i-S_i+2} \right] \cdots \left[ \tilde{Z}_{i,j}, X_{k_i-S_i+j} \right] \left[ \tilde{Z}_{i,j}^{*}, X_{k_i-S_i+j} \right] \right]$$

\(i = 0, 1, \cdots, S, \ j = 0, 1, \cdots, S \) and \(i + j \leq S, \) the volume of training data is $M_p = S(S+1)/2$.

In this paper, the time-delay compensation model can be pre-set as follows:

$$X_{k_i+S_i}=F_{i}(Z_{i})=\langle w, \Psi(Z_{i}) \rangle+b$$

where $w$ and $b$ are the trained parameters, which directly determine the performance of the time-delay error model.

Then, the function fitting problem is converted to the convex constrained optimization problem

$$\min \{ R(w, \xi_y, \xi_y^*) = \frac{1}{2} \| w \|^2 + C \sum_{i=1}^{N} (\xi_y + \xi_y^*) \} \quad \text{s.t.} \quad \begin{cases} X_i(j) - \langle w, \Psi(Z_{i}) \rangle - b(j) \leq \xi_y \ i = 1, \cdots, M \ j = 1, \cdots, 9 \end{cases}$$

where $\xi_y$ is called the called the tube size, which controls the error threshold for the target function. $C$ is the penalty factor regulating the tolerance between training error and the generalization ability. $\xi_y$ and $\xi_y^*$ represent the upper and lower error at point $[\tilde{Z}_{i}, \tilde{X}_{i}]$ in $A_{ep}$ or $A_{ip}$, $M$ is the volume of $A_{ep}$ or $A_{ip}$. The first term $\| w \|^2/2$ makes the target function smooth and therefore guarantees its generalization ability.

After that, the Lagrangian method is adopted to solve the optimization problem. The corresponding Lagrangian function for dual training is expressed as

$$\max L(\alpha, \alpha^*) = -\frac{1}{2} \sum_{i=1}^{M} \sum_{j=1}^{N} (\alpha_i - \alpha_i^*) (\alpha_j - \alpha_j^*) \langle \Psi(Z_{i}), \Psi(Z_{j}) \rangle - \sum_{i} (\xi_y - \tilde{X}_{i}) \alpha_i - \sum_{i} (\xi_y^* + \tilde{X}_{i}) \alpha_i^*$$

\(i, j = 1, 2, \cdots, M \)

where $\alpha$ and $\alpha^*$ are dual vectors whose corresponding elements are the Lagrange multipliers $\alpha_i$ and $\alpha_i^*$ in relationship with the constraints.

By solving Eq. (6), parameter $w$ is obtained and shown as:

$$w = \sum_{i=1}^{M} (\alpha_i - \alpha_i^*) \Psi(Z_{i})$$

Then, bringing Eq. (7) into Eq. (4), the target function is converted to:

$$F_{i}(Z_{i}) = \sum_{i=1}^{M} (\alpha_i - \alpha_i^*) \langle \Psi(Z_{i}), \Psi(Z_{i}) \rangle + b$$

To reduce the computational burden of dot product in the high dimension feature space for $\langle \Psi(Z_{i}), \Psi(Z_{i}) \rangle$, the dot product operation could be directly replaced by computing the so-called
kernel function \( G(\Psi(Z), \Psi(Z_j)) \), which is defined in the input space and satisfies the Mercer condition. The Gaussian RBF kernel function is selected in our study for parsimony and numerical convenience, which is shown as:

\[
G(\Psi(Z), \Psi(Z_j)) = \exp\left(-\frac{\|Z - Z_j\|}{2\sigma^2}\right)
\]  

(9)

where \( \sigma \) is the kernel width coefficient which controls the shape of this function. The final form of compensation model could be described as follows:

\[
\bar{X}_{k+\Delta t} = F_k(Z) = \sum_{i=1}^{N} (\alpha_i - \alpha'_i) \exp\left(-\frac{\|Z_k - Z_i\|}{2\sigma^2}\right) + b
\]

(10)

where \( \bar{X}_{k+\Delta t} \) is the predicted true output of POS at time \( t_k + \Delta t \) corresponding to the input \( Z_k \).

4. Experiment

In order to validate the proposed time-delay error compensation method, a flight experiment was carried out in December, 2015, Sanya City, Hainan Province, China. The equipment include an experiment plane (YUN-XII), aerial cameras, platform and RLG POS, which are equipped as Fig 2. As is introduced in this paper, the RLGs are dithered to prevent the effect known as lock-in, and the antivibration system and digital filter will bring in a long time-delay. The RLG POS used in this experiment is developed by Beihang University, which consists of an IMU and a Trimble 5700 dual-frequency GPS receiver. The IMU is composed of three RLGs with constant drift and random drift 0.01 and three quartz mechanical accelerometers with constant bias and random bias of accelerometers are 50. In addition, the post-processed position and velocity accuracy of GPS is 10 mm \( +1 \)ppm and 0.03 m/s, respectively. The sampling rates of IMU and GPS are 200 and 1 Hz, respectively.

The experiment, lasting about 3.58 hours, was carried out successively. Firstly, the experiment plane (YUN-XII) was still parked on airdrome for 300 seconds, the RLG POS began to sample data for initial alignment. Then, the plane was driven to flight along the programming course for high resolution aerial cameras. After completing the imaging task, the plane made a perfect landing on airdrome. The actual flight trajectory for aerial mapping is illustrated in Figure 3.

For analysing the proposed time-delay error compensation method, all flight data are analysed and the two methods are both carried out for comparison. As the results without time-delay is more precise than the delayed, we take the post-processing result without time-delay as the reference. The comparison results are shown below.
Comparison between Proposed method and conventional method, it can be seen that the accuracy of velocity and attitude are improved obviously. Besides, it can be learned that the proposed method can achieve better performance than the conventional one. The post-processing data compensated by the proposed method has been successfully applied to high accuracy camera imaging, and the ideal images are shown in Figure 7.
5. Conclusions
Position and orientation system (POS) has been widely applied to aerial cameras, imaging scanners, synthetic aperture radar, etc. As a multisensory system, time-delay usually occurs during signal preprocessing, transmission, integration, filtering, which undoubtedly decreases the measurement accuracy. As the POS motion parameter varies nonlinearly, the time-delay error can’t be precisely compensated by the conventional linear method. To solve this problem, a time-delay error compensation method of POS based on PSO tuning SVM was proposed for both post-processing compensation and real-time compensation. To validate the proposed method, the flight experiment has been carried out and the result shows that the proposed method can significantly reduce the time-delay error and is more accurate than the conventional method.

Acknowledgments
The work described in the paper was supported by National Natural Science Foundation of China under Grant 61571030, Grant 61421063, Grant 61703021, Grant 61473020, Grant 61763006 and Grant 61722103; the International (Regional) Cooperation and Communication Project under Grant 61661136007; the Aeronautical Science Foundation of China under Grant 20170551004.

References
[1] Cao Quan, Maiying Zhong, and Jianli Li. (2016)On Analytical Error Analysis of POS for Ground Alignment and Constant-Velocity Flight. IEEE Transactions on Instrumentation and Measurement 65.9: 2154-2162.
[2] Fang Jiancheng, Linzhouting Chen, and Jifeng Yao. (2014)An accurate gravity compensation method for high-precision airborne POS. IEEE Transactions on Geoscience and Remote Sensing 52.8: 4564-4573.
[3] Chen Linzhouting, and Jiancheng Fang. (2014)A hybrid prediction method for bridging GPS outages in high-precision POS application. IEEE Transactions on Instrumentation and Measurement 63.6: 1656-1665.
[4] Fang Jiancheng, and Yang Sheng. (2011)Study on innovation adaptive EKF for in-flight alignment of airborne POS. IEEE Transactions on Instrumentation and Measurement 60.4: 1378-1388.
[5] Stančić Rade, and Stevica Graovac. (2010)The integration of strap-down INS and GPS based on adaptive error damping. Robotics and Autonomous Systems 58.10: 1117-1129.
[6] Szadkowski, Zbigniew, and Dariusz Glas. (2016)Adaptive Linear Predictor FIR Filter Based on the Cyclone V FPGA with HPS to Reduce Narrow Band RFI in Radio Detection of Cosmic Rays. IEEE Transactions on Nuclear Science 63.3: 1455-1462.
[7] Jianli Li, et al. (2013)Time delay modeling and compensation of dithered RLG POS with antivibrators and filter. Measurement 46.6: 1928-1937.
[8] Li Jianli, Lidong Jia, and Gang Liu. (2016)Multisensor Time Synchronization Error Modeling and Compensation Method for Distributed POS. IEEE Transactions on Instrumentation and Measurement 65.11: 2637-2645.