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GNSS PPP/INS Integrated Precise Positioning and Attitude Determination with Comprehensive Error Analysis

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Abstract

GNSS Precise Point Positioning (PPP) has attracted widespread attention for its advantages of low cost and high precision at wide-area. However, the solution of PPP ambiguity parameters requires a long convergence time. Due to the inherent vulnerability of GNSS, frequent re-initialization under dynamic conditions seriously affects its positioning and navigation performance. To meet the current requirements, a multi-sensor integrated approach with high precision, high reliability, and high integrity has become a necessary trend for the development of the industry. Inertial Navigation System (INS) has the advantage of high precision in the short term, so it is complementary to GNSS and provides a solution to overcome the shortcomings of PPP in dynamic situations. As an essential scope of the multi-sensors integrated navigation systems research, PPP/INS has been studied and applied extensively. However, several core problems still need to be solved, mainly reflected in the high-reliability algorithms, weight determination of different systems, comprehensive error analysis methods, quality control and accuracy evaluation methods for the filtering process, and so on. Such problems are bottlenecks restricting the development and application of high-precision PPP/INS integrated systems, which have been the research hotspots and challenging topics in recent years. This thesis researches the problems mentioned above, and the main contents and contributions can be summarized as follows.

(1) Cycle slip detection is the premise to ensure the high precision positioning performance of PPP. Thus, a detailed error analysis is carried out for the INS-aided cycle-slip detection term. The specific influence of INS error on the cycle-slip detection term and detection performance are revealed, and the INS-aided cycle-slip detection terms suitable for PPP dynamic navigation application are constructed. Furthermore, a targeted detection threshold is derived. Experimental results show that the proposed algorithm can enhance the performance of PPP cycle-slip detection and reduce the risk of false alarms and missing detection.

(2) A PPP ambiguity resolution enhancement algorithm is proposed based on the virtual observation equation with INS position constrained. When GNSS signals are recaptured, the ambiguity parameters need to be reset. And the error accumulation of INS during the GNSS lock-out period will significantly affect the refixation of ambiguity parameters. From the error propagation analysis of INS independent navigation, a stochastic model for the virtual observation equation with INS position-constrained is constructed according to the time

of loss of lock. The stochastic model can more accurately reflect the characteristics of INS errors so that INS can always play a positive role in PPP ambiguity resolution process. Even if the INS error reaches several meters, it will not degrade the performance of the PPP itself. Based on this research, the enhanced ambiguity resolution strategy for the integrated system is discussed. And the PPP/INS integrated ambiguity resolution enhancement algorithm is subsequently proposed. Several measured vehicle navigation data have been used to evaluate the algorithm.

(3) The traditional Kalman filtering method only relies on the innovation vector for quality control and cannot fully consider the filter modeling error. A novel Kalman filtering process is used to achieve the unified posterior estimation of process noise, observation noise, and innovation vector. And the redundant observation factor of each noise can be accurately calculated by this process. A variance component estimation (VCE) method for the Kalman filter is proposed based on this, which comprehensively considers the redundant observation factors of various noise items and solves the problem of oversimplification of the previous VCE methods. The proposed method can directly estimate the variance components of the multi-source observations in the filter and realize the weight determination of the multi-source information. Taking multi-frequency and multi-system GNSS PPP static positioning as an example, the experimental analysis is carried out. The results show that the variance-covariance matrix of various observation and state-predicted values can be reasonably adjusted according to the calculated process noise residuals, observation residuals, and innovation vectors. And the positioning accuracy is improved significantly.

(4) A novel GNSS PPP/INS integration strategy is proposed employing the rigid body nonlinear kinematic equation. In the current GNSS/INS integrated filtering model, the observations of the two different systems are processed in the time update and measurement update processes, respectively. And the INS observation with errors directly constitutes the state transition matrix, which brings systematic errors but cannot be effectively eliminated. At the same time, the two systems cannot achieve the posterior estimation of the variance-covariance components. It is the only way to balance the contributions of different systems by tedious adjusting them through prior information and experience values. This thesis constructs a novel PPP/INS integrated state model and observation equation using the direct Kalman filtering method considering the kinematic relationship between state parameters. The new approach is more in line with the Kalman filtering theory. It has a more straightforward structure, which is convenient for providing dynamic model constraints for INS. It also can significantly reduce the impact of random drift of INS on the integrated system. At the same time, it is convenient to obtain a comprehensive error analysis of each noise in the filtering process and solve the weight determination problem for the different types of observation in the integrated system.

Keywords: GNSS PPP; INS; Integrated precise positioning and attitude determination; Kalman filter; Comprehensive error analysis; Novel integration strategy