

Research on the Theory and Methodology of GNSS/INS/Vision Resilient Fusion Navigation

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ABSTRACT

With the rapid development of technologies such as autonomous driving, unmanned aerial vehicles, and robotics, high-precision and reliable navigation services have become an indispensable core requirement and fundamental guarantee. However, in complex environments with obstructions and interference, a single navigation modality often fails to meet the demand for high-precision positioning across all regions and scenarios. Multi-source heterogeneous sensor fusion navigation, by leveraging the complementary characteristics of different sensors and jointly processing various types of observations, can effectively compensate for the limitations of individual sensors and is regarded as a key approach to achieving high-precision and highly available navigation services in challenging environments. At present, issues such as dynamic allocation of fusion weights for heterogeneous observations, as well as online estimation and optimization of noise parameters, remain bottlenecks that hinder the further advancement of multi-source fusion navigation technology. Motivated by this, this dissertation focuses on the theory and techniques of GNSS/INS/vision multi-source sensor fusion navigation and positioning, with global navigation satellite system (GNSS) technology as the foundation, targeting complex environments characterized by

obstructions and interference. The objective is to enhance the accuracy and robustness of navigation algorithms under such conditions. The main research contents and contributions of this work are as follows:

- (1). To address the inherent drawbacks of filter-based estimation algorithms, including cumulative linearization errors, limited model flexibility, and poor estimation consistency, a factor graph optimization (FGO) framework is employed, which offers more accurate handling of nonlinear models and stronger estimation consistency, thereby overcoming the limitations of filtering approaches. Within this framework, we propose a visual-inertial navigation system (FGO-VINS) and an FGO-based real-time kinematic (FGO-RTK) algorithm. Experimental results demonstrate that the proposed FGO-VINS achieves an average root mean square (RMS) absolute pose error (APE) of 0.132 m with a standard deviation (STD) mean of 0.057 m, significantly outperforming filtering-based frameworks such as ROVIO (RMS: 0.591 m, STD: 0.237 m) and MSCKF (RMS: 0.633 m, STD: 0.261 m). Compared with the EKF algorithm in RTKLIB, the proposed

FGO-RTK improves positioning accuracy by approximately 72.19%, 37.27%, and 47.36% in the east (E), north (N), and up (U) directions, respectively, while achieving an 84.9% increase in RTK ambiguity fixing rate.

- (2). To address the limitation of traditional visual-inertial navigation system, which model visual observation noise as fixed and thus struggle to adapt to dynamically changing environments, an adaptive weighted algorithm named Resilient-VINS is proposed. This method designs a strategy to quantify the credibility of feature points based on the characteristics and distribution of depth error in visual feature points. Accordingly, it dynamically adjusts the fusion weights of visual observations to achieve adaptive weighting for visual measurements. Experimental results demonstrate that, compared to the visual odometry and visual-inertial odometry of VINS-Fusion with fixed weights, Resilient-VINS improves the average positioning accuracy by 21.56% and 24.05%, respectively, with almost no additional computational cost or time overhead. The proposed approach effectively suppresses the influence of outlier observations, constrains trajectory divergence, and significantly enhances the system's accuracy and robustness.
- (3). To address the problem that rapid rotational motion of the platform tends to cause the accumulation of visual observation errors and system degradation, a bio-inspired adaptive visual-inertial navigation system (Bio-VINS) is proposed. By analyzing the stability indicators of visual feature tracking, the algorithm accurately identifies rapid rotational states of the platform and subsequently establishes a Gaussian-function-based adaptive weighting mechanism to intelligently adjust the fusion weights between visual and inertial measurements. Experimental results on the representative high-speed rotational dataset (V203) show that, compared with conventional visual-inertial navigation system, Bio-VINS

reduces the absolute pose error (APE) by approximately 30.33%, effectively mitigating performance degradation under rapid rotations. Moreover, it avoids over-optimization issues by requiring no excessive adjustment for standard datasets.

- (4). To mitigate the error accumulation and trajectory drift inherent in visual-inertial odometry (VIO), raw GNSS observations are further integrated, and a globally unbiased six-degree-of-freedom (6-DOF) tightly coupled GNSS/INS/visual pose estimation algorithm (GVINS) is proposed. Experimental results demonstrate that GVINS achieves sub-meter-level positioning accuracy when integrated with standard point positioning (SPP), and centimeter-level accuracy when integrated with real-time kinematic (RTK). In simulated sensor degradation scenarios, GVINS maintains a positioning error within 5 m even under GNSS signal outages of up to 300 seconds; upon signal recovery, the horizontal and vertical positioning errors quickly converge to 0.585 m and 0.486 m, respectively.
- (5). To address the violation of the “rigid scene assumption” caused by dynamic objects in visual imagery, which leads to feature mismatches, pose estimation biases, and point-cloud map distortions, a real-time online visual dynamic feature recognition and elimination multi-source fusion navigation algorithm (Dyna-GVINS) is proposed. This algorithm incorporates a lightweight visual semantic segmentation module combined with epipolar constraint and geometric consistency checking, enabling accurate online identification and elimination of dynamic features in real time. Experimental results demonstrate that, compared with conventional multi-source fusion algorithms, Dyna-GVINS improves positioning accuracy by approximately 18.6%, 14.3%, and 53.5% in the east (E), north (N), and up (U) directions, respectively, while increasing the RTK ambiguity fixing rate by 23.48%.

(6). To address the susceptibility of GNSS signals to multipath effects and non-line-of-sight (NLOS) errors in urban canyon environments, a novel RTK (Real-Time Kinematic) stochastic model tailored for such conditions is developed. The proposed model employs the code-minus-phase (CMP) metric to characterize the residual noise of pseudo-range observations, based on which a gradient function model is constructed to adaptively adjust the weights of pseudo-range measurements. This approach effectively mitigates the influence of multipath and NLOS errors on positioning, thereby improving the utilization of GNSS observations. Experimental

results indicate that, compared with the conventional elevation-angle-based stochastic model in RTK/INS/vision multi-source fusion navigation, the proposed method improves positioning accuracy by approximately 21.9%, 15.0%, and 42.7% in the east (E), north (N), and up (U) directions, respectively, while enhancing the RTK ambiguity fixing rate by about 42.1%.

Key words: GNSS, visual-inertial navigation, integrated navigation, multi-source fusion, factor graph optimization