FE-GUT: Factor Graph Optimization hybrid with Extended Kalman Filter for tightly coupled GNSS/UWB Integration

Qijia Zhao[1], ShaoLin Lü[2], Jianan Lou[1], Rong Zhang[1*]

[1]*Department of Precision Instrument, Tsinghua University*

[2]*Graph Optimization Inc.*

Beijing, China

rongzh@mail.tsinghua.edu.cn

Abstract—The continuous development of the consumer electronics market has stimulated an increasing demand for low-cost and precise positioning services. Naturally, Global Navigation Satellite System (GNSS) receivers has become essential in modern society. Due to some deficits of GNSS, such as susceptible to interferences, the integration of GNSS and additional alternative sensors is a promising approach to overcome the performance limitations of GNSS-based localization systems. Ultra-Wideband (UWB), a carrier-less communication technology with nanosecond-level time resolution, offers many excellent characteristics, including high transmission rates, strong multipath capability, and interference resistance. Since low-cost UWB devices can achieve centimeter-level ranging accuracy in harsh environments, many interests are sparked in GNSS/UWB integration. However, since most pre-packaged UWB devices lack a synchronization interface, hardware-based time synchronization is usually undesirable. Due to the foresaid reason, online temporal calibration is highly required for the tightly coupled GNSS/UWB integration.

Nowadays, Extended Kalman Filter (EKF) is regarded as the de facto benchmark algorithm for most state estimation problems. Traditionally, when EKF was used, there was an implicit assumption that all the system states were discretized at the same frequency. After all, EKF is a small-scale algorithm which cannot handle large-scale data per update. However, this assumption may not be obeyed when Factor Graph Optimization (FGO), which can handle larger-scale data, is used. In many scenarios, it has been verified that the different system states can be discretized at different frequencies from the continuous-time model.

Graphical State Space Model (GSSM) is a relatively novel method by which the slowly changing or constant variables are discretized at a low frequency. When this approach fits the nature of system states very well, it will improve the state estimation performance. GSSM has successfully inspired a bunch of applications, such as Real-Time Kinematic (RTK) positioning, INS/GNSS integration, and etc.

Since the computer clocks drift slowly, the time-offset between GNSS and UWB measurements is considered a constant for a certain period of time. When the tightly coupled GNSS/UWB integration is modeled by GSSM and solved with FGO, it will be found that the constant time-offset estimation will be significantly more precise and robust than that gotten by EKF. At the same time, it is frustrating that the accuracy of position and velocity estimation will be either equal to or sometimes even worse than that gotten by EKF. Factor graph of GSSM is shown in Fig. 1. These influences by different discretization methods are interesting, perplexing and utterly important. We will elucidate the theorical reasons for these phenomena in the future works. Currently, it is apparent that an architecture with a hybrid of FGO and EKF can effectively leverage the respective merits of both methods.

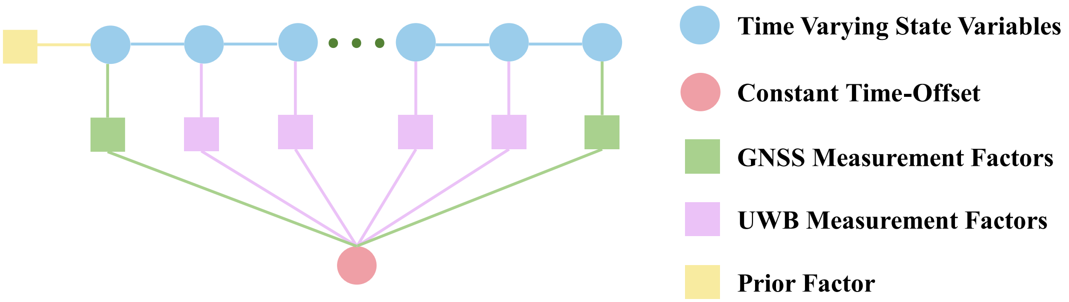

Fig. 1. The factor graph of the tightly coupled GNSS/UWB integration modeled by GSSM.

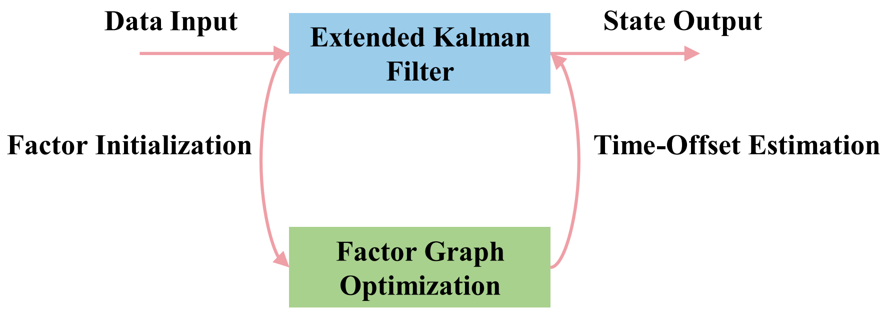

Fig. 2. The flow chart of FE-GUT.

In this work, a novel architecture in which FGO is hybrid with EKF for tightly coupled GNSS/UWB integration with online Temporal calibration (FE-GUT) is proposed. The flow chart of FE-GUT is shown in Fig. 2. Firstly, since FGO is sensitive dependence on the initial conditions, the new factors incorporated into the sliding window are initialized by a naive EKF without the time-offset calibration. The naive EKF can provide an well-initialized value close to the global optimum and prevent the solution obtained by FGO from getting trapped in a local optimum. Secondly, GSSM, which models the time-offset as a constant, is solved by FGO which incorporates all the system states. In this paper, the Ceres Solver is utilized in the C++ implementation to solve the non-linear optimization problem. GSSM leads to better estimation of the time-offset than EKF. Finally, the time-offset obtained from GSSM can be fed back to the naive EKF. In the dynamic system model, a constant acceleration model is adopted to compensate for the UWB ranging error introduced by the time-offset.

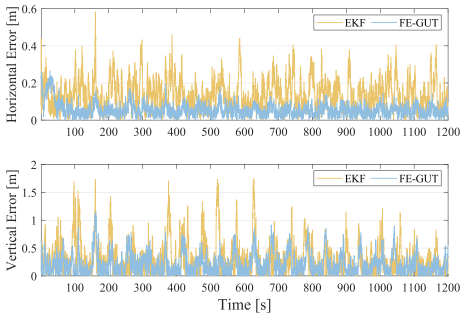

Fig. 3. The localization error comparison.

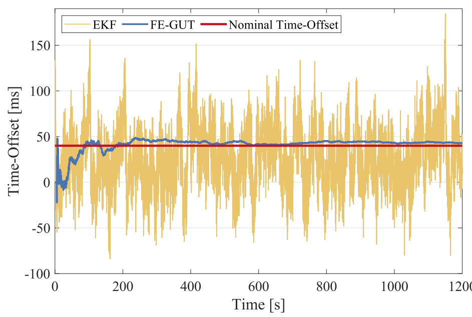

Fig. 4. The estimated time-offset comparison.

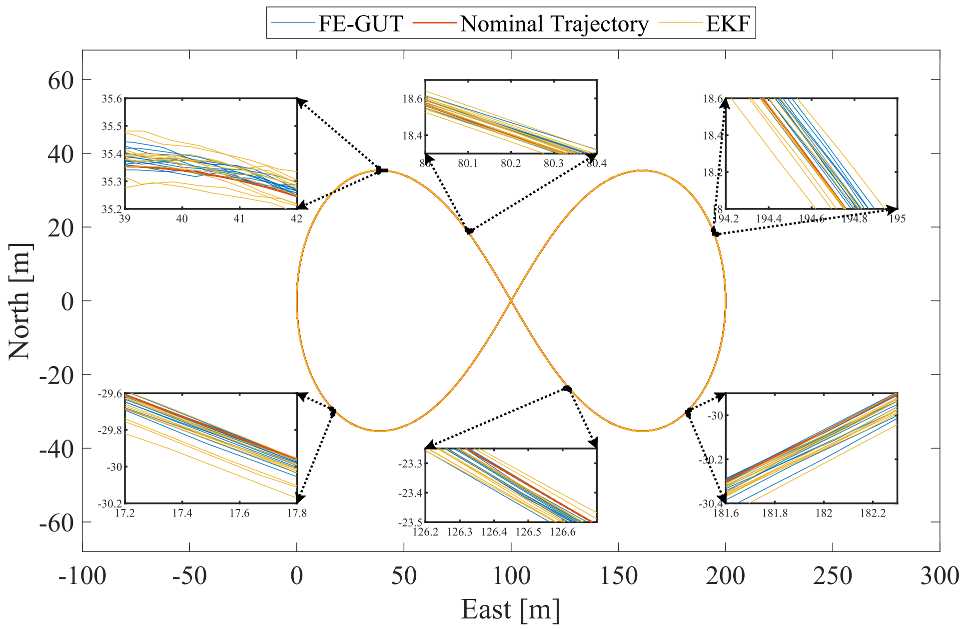

Fig. 5. The nominal and estimated trajectories.

Simulation-based experiments are conducted to validate the integrated localization performance by FE-GUT. In the four-wheeled robot scenario, the results demonstrate that when compared with EKF, FE-GUT can improve the horizontal and vertical localization accuracy respectively by 58.59% and 34.80%, while the time-offset estimation accuracy can be improved by 76.80%. Especially, for the selected measurement settings, FE-GUT can improve the horizontal positioning accuracy from the decimeter level to the centimeter level.

In Fig. 3, the positioning error in both horizontal and vertical directions are compared for FE-GUT and EKF. In Fig. 4, the time-offset estimation results by FE-GUT are compared with those by EKF. In Fig. 5, the nominal and estimated trajectories are illustrated in details. It can be concluded that the positioning results gotten by FE-GUT are more precise than those gotten by EKF. All the source codes and datasets can be gotten via https://github.com/zhaoqj23/FE-GUT/.

The structure of the paper is organized as follows. In Section II, a brief introduction to GSSM is presented. In Section III, the traditional discrete-time state space model and GSSM for tightly coupled GNSS/UWB integration is introduced. Besides, we introduce the procedure of FE-GUT and demonstrate how FGO and EKF are bridged. In Section IV, FE-GUT are compared with EKF in the positioning and time-offset estimation performance for a four-wheeled scenario. Conclusions and future works are presented in Section V.

This work can inspire for future research from two perspectives. First, the effectiveness of GSSM is further demonstrated and its application range is expanded. Although GSSM solved by FGO can not outperform EKF for all variables on this matter, it can still be used to promote EKF. Obviously, FGO and EKF are not in conflict with each other. The combination of these two algorithms may sometimes breed a brand-new and high-accuracy solution.