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# Study and Design of Bayesian Methods for GNSS in Challenging Environments

By

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# Abstract

Reliable and accurate positioning, navigation and timing (PNT) services are increasingly critical for modern applications, from everyday consumer devices and intelligent transportation systems to safety-critical autonomous platforms, resilient communication networks, and emerging space exploration missions. While Global Navigation Satellite Systems (GNSSs) provide a global infrastructure for PNT, satellite-based positioning still faces significant challenges in harsh environments. In terrestrial contexts, dense urban canyons or signal-obstructed areas can severely compromise both the quality of the available measurements and their overall availability, thereby reducing accuracy and continuity in single-point position, velocity, timing (PVT) estimation. In spaceborne applications, extending GNSS-based navigation beyond the operational limits of the space service volume (SSV) presents unprecedented hurdles; these include sparse navigation signal availability, predominant tracking of weak signal side lobes, and poor satellite geometries. This dissertation addresses these challenges under the unifying lens of Bayesian estimation and sequential filtering, proposing methods to enable accurate, continuous, and reliable navigation across both terrestrial and deep space scenarios.

A central contribution is the tight integration of GNSS and ultra-wide band (UWB) technologies, leveraging UWB's high-precision short-range ranging and strong multipath resilience to improve PVT performance. Beyond enhanced measurement accuracy, UWB also provides complementary system observability in GNSS-denied environments, thereby increasing the overall robustness of the navigation solution. Two key challenges are addressed. First, the highly nonlinear nature of the short-range UWB measurement model is investigated by analyzing the performance degradation of the Extended Kalman Filter (EKF) and comparing it against a sampling-importance-resampling (SIR)-based Particle Filter (PF). This comparative analysis provides practical guidelines for selecting the most appropriate Bayesian filter based on the expected receiver dynamics, the required navigation accuracy, and the available computational resources. Second, asynchronous sensor integration is tackled through a double-update EKF architecture, where the GNSS/UWB time offset is explicitly modeled and jointly estimated as part of the filter state. The proposed framework incorporates an adaptive tuning strategy for the UWB noise model, which enhances time offset observability and improves time calibration performance.

The proposed GNSS/UWB integration is further validated through a real-world demonstrator of multi-robot collaborative navigation. In this setup, the PNT unit of an unmanned ground vehicle (UGV) operating under satellite signal obscuration is locally aided by an unmanned aerial vehicle (UAV) providing opportunistic ranging. Auxiliary measurements are directly obtained through UWB-based ranging, or constructed using GNSS-based differential baseline estimation using double difference (DD) combinations to overcome line-of-sight (LoS) constraints. These auxiliary measurements are tightly integrated with local GNSS observables within a centralized hybrid EKF onboard the UGV, designed for modularity, low computational cost, and scalability to larger collaborative fleets, enabling enhanced PNT performance and mission autonomy in support of beyond visual line-of-sight (BVLoS) operations.

In space applications, the research extends GNSS capabilities to support autonomous navigation in cislunar space, with the goal of reducing dependence on Earth-based tracking systems while ensuring computational feasibility for resource-constrained onboard systems. A semi-autonomous, trajectory-aided Bayesian filtering method is first proposed, combining onboard GNSS observations with orbit predictions computed on the ground and preloaded via the Telemetry, Tracking and Command (TT&C) link. Within this framework, the aiding information is flexibly assimilated into the Trajectory-Aware EKF (TA-EKF), either as prior knowledge in the prediction step (state-domain) or as an auxiliary observation in the correction step (observation-domain). These dual formulations, which are analytically equivalent, enable the integration of diverse auxiliary data sources, not limited to trajectory priors. The TA-EKF bridges the gap between lightweight single point positioning methods and filtered orbit determination (OD) with computationally intensive orbit propagators. It achieves estimation accuracy comparable to the latter while leveraging low-complexity polynomial motion models suitable for (near) real-time onboard implementation.

In advancing GNSS-based OD toward full autonomy, this dissertation investigates two complementary estimation strategies tailored to the challenging operational conditions of cislunar space. The first is a dynamic approach based on sequential Bayesian filtering with an orbit propagator, where the performance of the established EKF-based Orbital Filter (OF) is reassessed in low lunar orbit (LLO), a regime where reduced state observability and highly nonlinear dynamics can undermine estimation accuracy. A Unscented Kalman Filter (UKF)-based architecture, employing sigma-point orbit propagation, demonstrates improved accuracy, confirming the benefits of more advanced Gaussian filters for deep space navigation. The second approach addresses single point positioning through a novel batch estimator based on Tikhonov-regularized Gauss-Newton (GN) with prior constraints, jointly processing code and carrier-phase measurements. Tailored for single-frequency precise point positioning (SF-PPP), the proposed method mitigates underdetermined and ill-conditioned measurement geometries, enabling dynamic-model-free (i.e., purely kinematic) precise orbit determination (POD) with promising accuracy and availability across the cislunar space, including at lunar altitudes and on the Moon's surface. Overall, the unified Bayesian filtering framework proposed herein provides a versatile and scalable solution to the current and emerging challenges of GNSS-based navigation across both terrestrial and spaceborne domains, paving the way to further advancements in resilient and autonomous navigation systems both on Earth and in deep space.