Continuous-Time Ultra-Wideband-Inertial Fusion

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Abstract

We introduce a novel framework of continuous-time ultra-wideband-inertial sensor fusion for online motion estimation. Quaternion-based cubic cumulative B-splines are exploited for parameterizing motion states continuously over time. Systematic derivations of analytic kinematic interpolations and spatial differentiations are further provided. Based thereon, a new sliding-window spline fitting scheme is established for asynchronous multi-sensor fusion and online calibration. We conduct a dedicated validation of the quaternion spline fitting method, and evaluate the proposed system, SFUISE (spline fusion-based ultra-wideband-inertial state estimation), in real-world scenarios using public data set and experiments. The proposed sensor fusion system is real-time capable and delivers superior performance over state-of-the-art discrete-time schemes. We release the source code and own experimental data at `https://github.com/ASIG-X/SFUISE`.

Background

Recent advancements in UWB technology have offered promising alternative solutions to localization in GPS-denied environments, ideal for indoor scenarios due to their low cost, scalability, and lightweight nature. However, technical issues such as non-line-of-sight, multipath conditions, and non-Gaussian noise patterns persist, making high-performance and reliable UWB-based tracking still very challenging in practice. These issues can be mitigated by deploying inertial measurement units (IMUs) to provide instantaneous and higher-order motion information. In this work, we focus on continuous-time state estimation based on UWB-inertial fusion.

Contributions

- SFUISE - Spline Fusion-based Ultra-wideband-Inertial State Estimation
- Quaternion-based cubic cumulative B-splines for continuous-time 6-DoF pose representation + Analytic kinematic interpolations and Jacobians w.r.t. control points
- Efficient sliding-window spline fitting scheme for UWB-inertial fusion at raw time instants in real time + option for online calibration
- Extensive real-world evaluations for UWB-inertial tracking (ToA & TDoA)
- Open-source implementation together with own experimental datasets

State Estimation on B-Splines

We deploy cubic cumulative B-splines for continuous-time state representation

$$\underline{x}(t) = [\underline{r}(t)^\top, \underline{s}(t)^\top, \underline{b}(t)^\top]^\top, \quad \text{with control points} \quad \underline{x} = [\underline{q}^\top, \underline{p}^\top, \underline{b}^\top]^\top \in \mathbb{R}^{13}.$$

States at arbitrary time instants can be interpolated w.r.t. a local set of knots as follows

$$\text{quaternion state} \quad \underline{r}(t) = \underline{q}_{i-2} \otimes \prod\nolimits_{j=1}^{3} \mathrm{Exp}_{\mathbb{1}}\left(\lambda_j(u)\,\underline{\delta}_j\right),$$

$$\text{linear state} \quad \underline{s}(t) = \underline{p}_{i-2} + \sum\nolimits_{j=1}^{3} \lambda_j(u)\,\underline{\delta}_j.$$

Sliding-Window Spline Fitting

For online performance, we formulate the sensor fusion problem in the form of optimization over a window of recent τ_{w} knots $\mathcal{X}_{\mathrm{w}} = [\underline{x}_1, ..., \underline{x}_{\tau_{\mathrm{w}}}] \in \mathbb{R}^{13\times\tau_{\mathrm{w}}}$, namely,

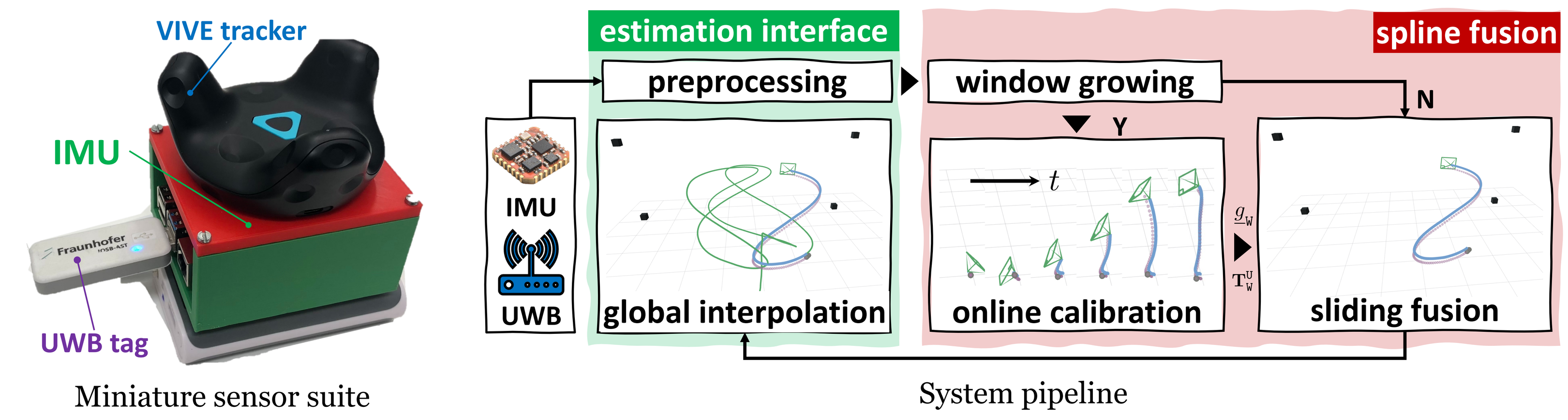
$$\mathcal{X}_{\mathrm{w}}^\star = \arg\min_{\mathcal{X}_{\mathrm{w}}} \mathcal{F}(\mathcal{X}_{\mathrm{w}}).$$

The objective function incorporating UWB and IMU residuals is formulated as

$$\mathcal{F}(\mathcal{X}_{\mathrm{w}}) = \upsilon_{\mathrm{u}} \sum_{i=1}^{m} \|\mathscr{E}_{\mathrm{u}}(\mathcal{X}_{\mathrm{w}}, \hat{z}_{\mathrm{u},i})\|^2_{\mathbf{C}_{\mathrm{u}}} + \upsilon_{\mathrm{i}} \sum_{k=1}^{n} \|\mathscr{E}_{\mathrm{i}}(\mathcal{X}_{\mathrm{w}}, \hat{\underline{z}}_{\mathrm{i},k})\|^2_{\mathbf{C}_{\mathrm{i}}}.$$

System Design

The system SFUISE composes an estimation interface and a functional core of sliding-window spline fitting. As UWB and IMU measurements arrive, a cumulative B-spline composing the continuous-time states is fitted first over a window-growing stage together with the online calibrations and afterward over sliding windows. Resulting estimates are sent back to estimation interface for visualization.

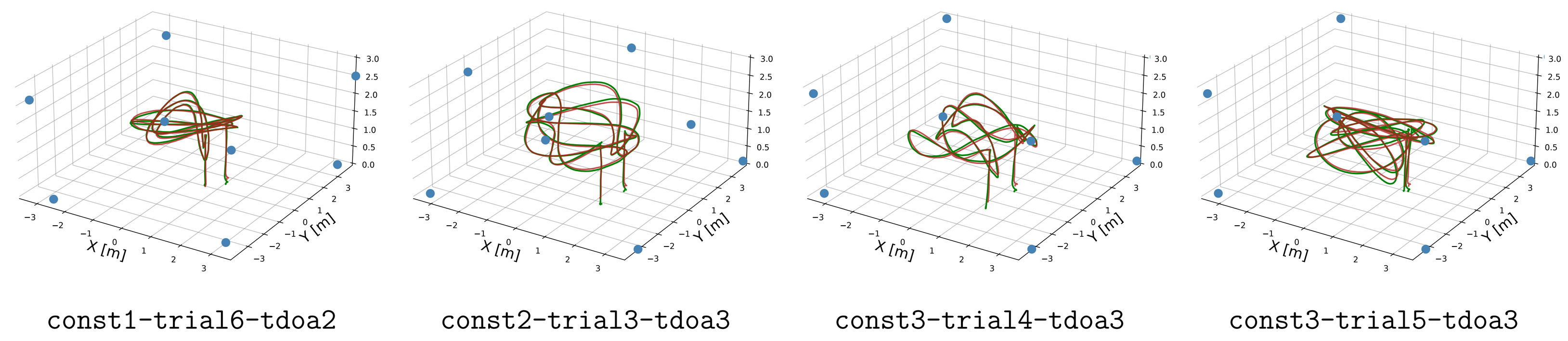


Miniature sensor suite System pipeline

To evaluate the proposed scheme on UWB-inertial fusion, a miniature sensor suite based on time-of-arrival (ToA) ranging has been instrumented. It is composed of a UWB tag and an IMU, both mounted to a Raspberry Pi for sensor coordination and data recording. An additional VIVE tracker is added to provide the ground truth.

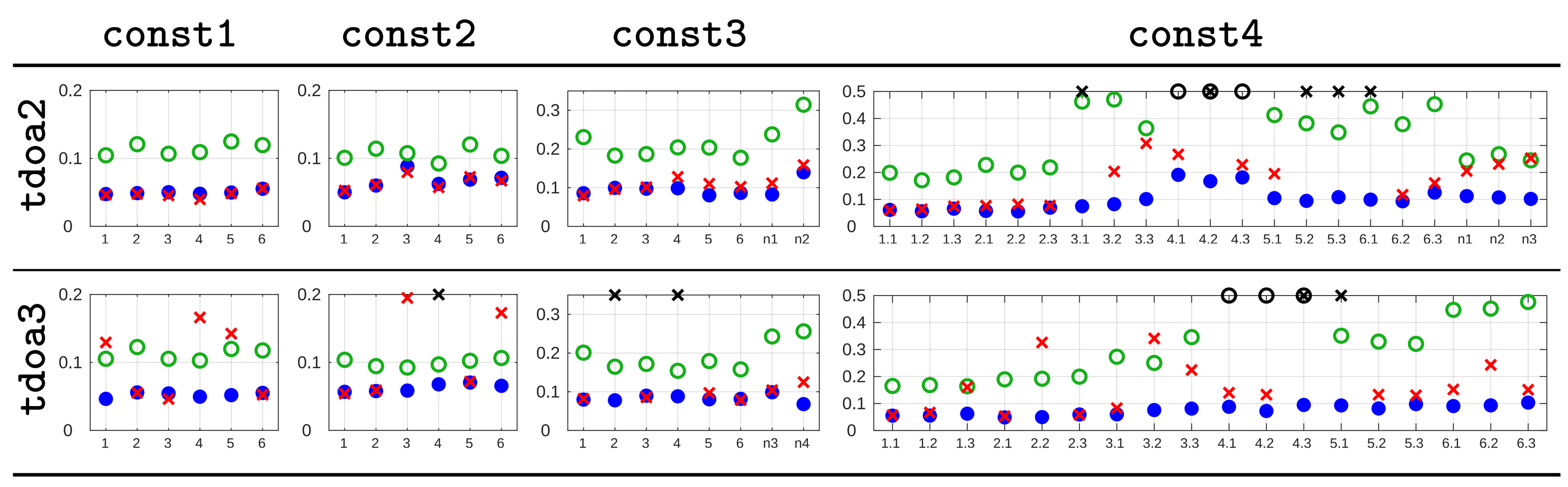
Evaluation & Conclusion

SFUISE has been evaluated in real-world scenarios based on the public dataset `UTIL` (utiasdsl.github.io/util-uwb-dataset) and own experiments with our miniature suite, incorporating both ToA and TDoA UWB data.



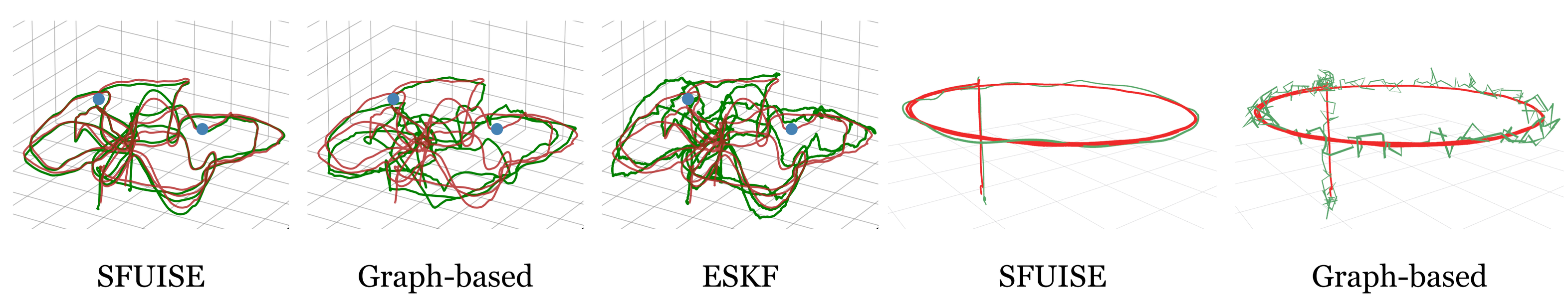
Exemplary runs of SFUISE on `UTIL`

Two major discrete-time sensor fusion schemes of state of the art are considered for comparison: (1) an own composition of graph-based UWB-inertial fusion system (similar to VINS-Mono) and (2) an error-state Kalman filter (ESKF) provided by `UTIL`.



APEs (RMSE) obtained from benchmark on all sequences of `UTIL` dataset. Results from SFUISE are plotted with •. Results from ESKF and the graph-based methods are given by ∘ and ×, with ∘ and × indicating tracking fails, respectively.

The strength of spline fusion can be further highlighted in UWB-only tracking. The proposed spline-based scheme delivers motion estimates of inherent kinematic consistency in an efficient representation. We look forward to further establishing the continuous-time paradigm in areas of planning, control, odometry and mapping, etc.



Comparisons with discrete-time methods UWB-only tracking

Find our open-source implementation & Visit our group's homepage:

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