Visual-Inertial Localization with Prior LiDAR Map Constraints

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Motivation

- Micro air vehicles (MAV) are resource constrained with small sensor payload limits
- Leverage low-cost light-weight stereo visual-inertial sensors for estimation
- Leverage *a priori* point map information to bound estimation drift
- Focus on cross-modal constraints between semi-dense stereo and LiDAR prior pointclouds

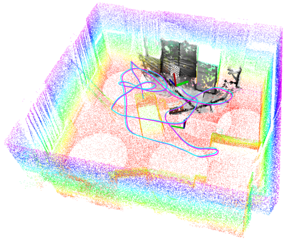


Figure 1: EurocMav prior LiDAR map with example semi-dense stereo reconstruction.

Contributions

- Design of a *tightly-coupled* MSCKF-based filter for low-cost multi-modal 6DOF pose estimation.
- Find global pose constraints through NDT registration of semi-dense stereo reconstruction and the prior LiDAR map.
- Handle covariance of registration and investigate sensitivity to prior map inaccuracies.
- Validate proposed system in simulation and real-world datasets and show superior performance over state-of-the-art.

System Overview

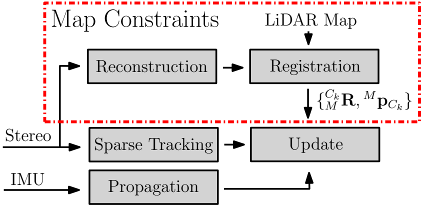


Figure 2: Data flow and proposed map constraint generation.

- System composed of two main parts: (i) sparse feature tracking, (ii) semi-dense reconstruction and registration.
- Sparse feature tracks allow for fast ego-motion estimation and locally accurate estimates.
- Registration to the prior map limits provides globally accurate estimates with little drift.

Semi-Dense Reconstruction

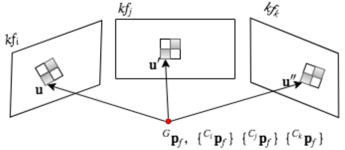


Figure 3: Depth correspondence matching.

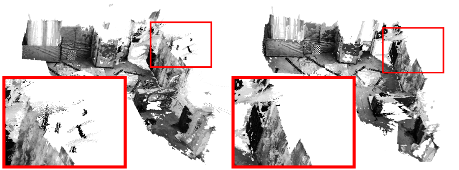


Figure 4: Without depth refinement (left). With depth refinement (right).

- Select keyframes with large baseline for refinement
- Refine depths by finding matches in other keyframes
- Prune noisy points in reconstructed pointcloud

Normal Distribution Transform (NDT) Registration

- Use point-to-distribution (P2D) of NDT to optimize map transformation $\{{}^{C_k}_{M}\mathbf{R}, {}^{M}\mathbf{p}_{C_k}\}$ of semi-dense reconstruction
- Covariance can be found through inverse of cost function's Hessian matrix
- Can directly update filter as we additionally estimate the transformation between map and VIO frame $\{{}^{G}_{M}\mathbf{R}, {}^{M}\mathbf{p}_{G}\}$

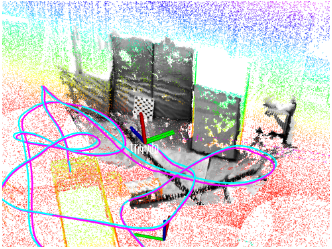


Figure 5: Example registration to prior map.

Simulation Results I

- Simulated 836m vehicle trajectory in Gazebo with realistic sensor noise values where used.
- System shows accuracy improvement when including prior map constraints over odometry method.

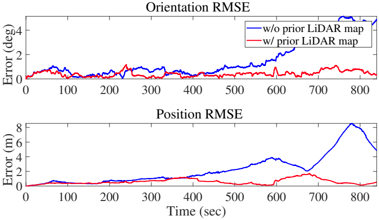


Figure 6: Orientation and position RMSE for the standard MSCKF and map-aided MSCKF with prior LiDAR map noises of $\sigma = 0.03m$).

Simulation Results II

Table 1: Trajectory RMSE with different levels of prior map noises.

RMSE	MSCKF	MSCKF w/ Map $\sigma = 0.03m$	MSCKF w/ Map $\sigma = 0.30m$	MSCKF w/ Map $\sigma = 0.40m$	MSCKF w/ Map $\sigma = 0.50m$
Position (m)	3.19	1.26	2.33	3.08	3.24
Orientation (deg)	2.77	1.11	1.87	2.22	2.94

- Looking at sensitivity to noisy prior maps, system is robust to large amounts of noise.
- Only after $> 0.40m$ noise the filter degrades to standard MSCKF accuracy.

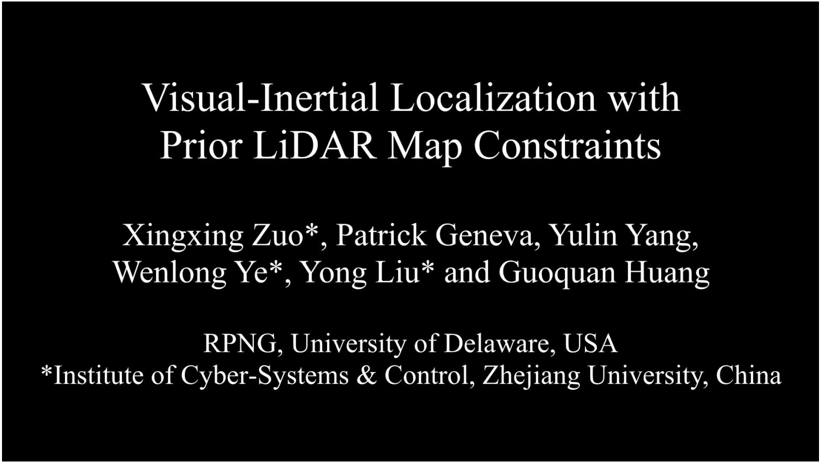
Real-World Results - EurocMav

- Evaluated with provided LiDAR maps of EurocMav Vicon rooms
- Estimation occurs at 30Hz with prior map loop-closures at 1.25Hz
- Outperforms VINS-Mono with and without loop-closure

Table 2: Relative pose error for different segment lengths.

Segment Length	MSCKF	MSCKF w/ Map	VINS-Mono (odom)	VINS-Mono (loop)
7m	**0.136**	0.143	0.162	0.156
14m	**0.148**	0.154	0.180	0.160
21m	0.194	**0.184**	0.233	0.208
28m	0.202	**0.175**	0.246	0.223
35m	0.237	**0.191**	0.273	0.260

System Demonstration



Conclusion

- Proposed inclusion of cross-modal prior map constraints in MSCKF framework.
- Leveraged NDT registration of semi-dense reconstruction to prior pointcloud.
- System shows robustness to prior map noises.
- Outperforms state-of-the-art due to inclusion of prior map constraints
- Base system used, OpenVINS, has been open sourced: https://github.com/rpng/open_vins