FEJ2: A Consistent Visual-Inertial State Estimator Design

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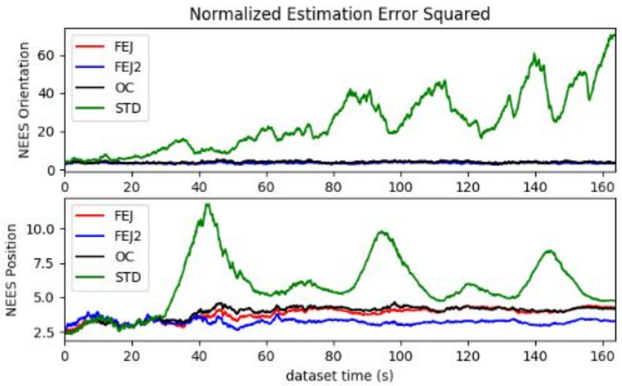
Introduction

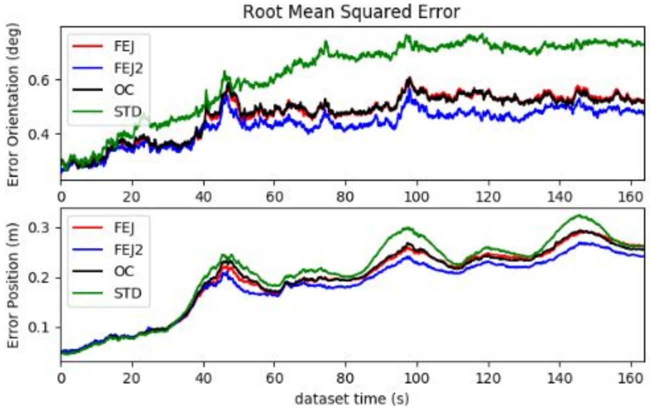
- Filter-based visual-inertial estimators
  - 4 d.o.f unobservable ideally (yaw + pos.)
  - linearizing at current state estimates causes information gains in unobs.
  - Covariance becomes overconfident (inconsistent)

- First-estimates Jacobian (FEJ)
  - Fixes Jacobians at first estimates to enforce 4 d.o.f (consistent)
  - Fixes Jacobians introduce unmodelled errors

- We propose ***FEJ2***
  - Addresses the unmodelled errors of FEJ
  - Shown to improve performance

NEES is large since covariance is overconfident





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[2] Hesch, Joel A., et al. "Camera-IMU-based localization: Observability analysis and consistency improvement." The International Journal of Robotics Research 33.1 (2014): 182-201.
[3] Huang, Guoquan P., Anastasios I. Mourikis, and Stergios I. Roumeliotis. "Observability-based rules for designing consistent EKF SLAM estimators." The International Journal of Robotics Research 29.5 (2010): 502-528.

Estimator Design

$$\begin{aligned}
\mathbf{z} &= \mathbf{h}(\mathbf{x}) + \mathbf{n} \\
&\simeq \mathbf{h}(\hat{\mathbf{x}}) + \hat{\mathbf{H}}\tilde{\mathbf{x}} + \mathbf{n} \\
&\simeq \mathbf{h}(\hat{\mathbf{x}}) + \bar{\mathbf{H}}\tilde{\mathbf{x}} + \mathbf{n} \\
&= \mathbf{h}(\hat{\mathbf{x}}) + (\bar{\mathbf{H}} + \hat{\mathbf{H}} - \bar{\mathbf{H}})\tilde{\mathbf{x}} + \mathbf{n} \\
&= \mathbf{h}(\hat{\mathbf{x}}) + \bar{\mathbf{H}}\tilde{\mathbf{x}} + (\hat{\mathbf{H}} - \bar{\mathbf{H}})\tilde{\mathbf{x}} + \mathbf{n} \\
&= \mathbf{h}(\hat{\mathbf{x}}) + \bar{\mathbf{H}}\tilde{\mathbf{x}} + \Delta\mathbf{H}\tilde{\mathbf{x}} + \mathbf{n}
\end{aligned}$$

$$\hat{\mathbf{r}} = \mathbf{z} - \mathbf{h}(\hat{\mathbf{x}}) \simeq \bar{\mathbf{H}}\tilde{\mathbf{x}} + \Delta\mathbf{H}\tilde{\mathbf{x}} + \mathbf{n}$$

$$\Delta\mathbf{U}^\top\hat{\mathbf{r}} = \Delta\mathbf{U}^\top\bar{\mathbf{H}}\tilde{\mathbf{x}} + \cancel{\Delta\mathbf{U}^\top\Delta\mathbf{H}\tilde{\mathbf{x}}} + \Delta\mathbf{U}^\top\mathbf{n}$$

$$\Rightarrow \boxed{\mathbf{r}^* = \mathbf{H}^*\tilde{\mathbf{x}} + \mathbf{n}^*}$$

FEJ

- Evaluate the measurement Jacobian at the first state estimate
- Assumes $\Delta\mathbf{H}$ is ***zero*** to improve consistency
- Introduce unmodelled errors

FEJ2

- $\Delta\mathbf{H} = \hat{\mathbf{H}} - \bar{\mathbf{H}}$ captures linearization point changes between the ***first*** and ***best*** state estimates
- Project onto the nullspace of $\Delta\mathbf{H}$ to remove
- Keeps the ***correct*** unobservable subspace
- Better consistency than FEJ

Results and Conclusion

- Simulate inertial and bearing measurements under different VINS frameworks
- Monocular and stereo measurements
- Different measurement noise

Noise (pixel)	Est.	RMSE Ori. (deg) mono / stereo	RMSE Pos. (m) mono / stereo	NEES Ori. mono / stereo	NEES Pos. mono / stereo
1	STD	0.412 / 0.344	0.130 / 0.109	23.874 / 15.447	4.911 / 4.874
	OC	0.242 / 0.257	0.119 / 0.100	3.290 / 3.599	3.540 / 3.416
	FEJ	0.242 / 0.256	0.120 / 0.100	3.284 / 3.438	3.617 / 3.322
	FEJ2	**0.238 / 0.238**	**0.118 / 0.095**	**3.150 / 3.324**	**3.443 / 2.965**
3	STD	2.139 / 0.888	0.402 / 0.310	407.221 / 33.852	13.212 / 7.235
	OC	0.716 / 0.723	0.301 / 0.300	3.964 / 4.395	5.051 / 4.839
	FEJ	0.861 / 0.704	0.289 / 0.298	4.965 / 4.163	4.763 / 4.656
	FEJ2	**0.650 / 0.663**	**0.264 / 0.277**	**3.198 / 3.790**	**3.581 / 3.636**

FEJ2 achieves better consistency and accuracy!

Summary

- Develop a novel **consistent** estimator design for VINS
- FEJ2 **accurately** models linearization errors of FEJ
- Theoretical proofs, simulations and real-world experiments show FEJ2 achieves **better performance**

Thank you!

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