NRI: FND: Consistent Distributed Visual-Inertial Estimation and Perception for Cooperative Unmanned Aerial Vehicles

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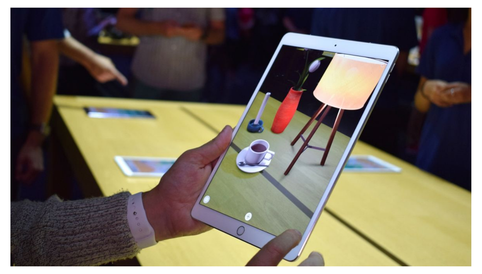
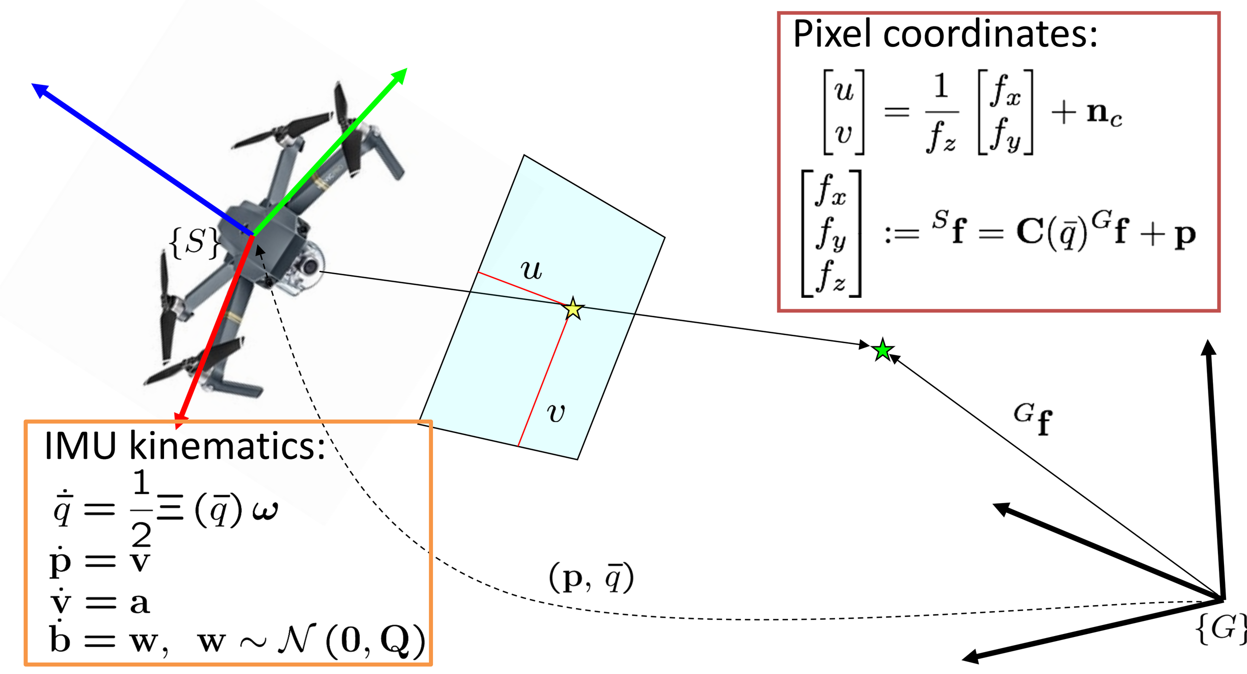
https://sites.udel.edu/robot/

1. Visual-inertial estimation

- Visual-inertial navigation system (VINS) or SLAM holds great potentials in practical applications:



- Goal: To estimate 3D motion & scene understanding using IMUs and cameras onboard unmanned aerial vehicles (UAVs)



Pixel coordinates:

$$\begin{bmatrix} u \\ v \end{bmatrix} = \frac{1}{f_z}\begin{bmatrix} f_x \\ f_y \end{bmatrix} + \mathbf{n}_c$$

$$\begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix} := {}^S\mathbf{f} = \mathbf{C}(\bar{q})\,{}^G\mathbf{f} + \mathbf{p}$$

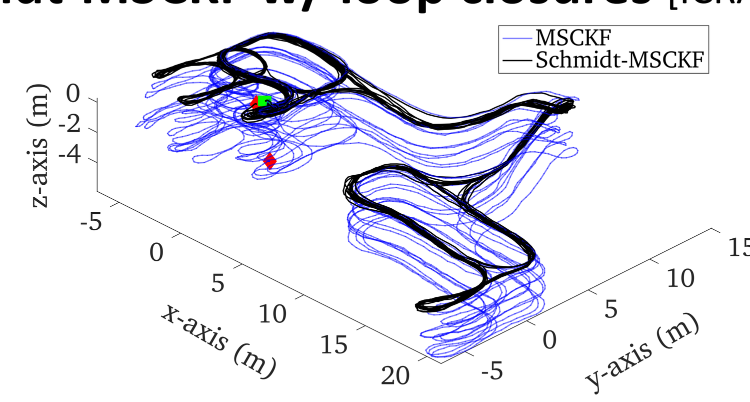
IMU kinematics:

$$\dot{\bar{q}} = \frac{1}{2}\Xi(\bar{q})\,\omega$$
$$\dot{\mathbf{p}} = \mathbf{v}$$
$$\dot{\mathbf{v}} = \mathbf{a}$$
$$\dot{\mathbf{b}} = \mathbf{w}, \quad \mathbf{w} \sim \mathcal{N}(0, \mathbf{Q})$$

- **Technical challenges when extending to multi-UAVs:**
  - ❑ Consistent, distributed, cooperative visual-inertial estimation under resource constraints

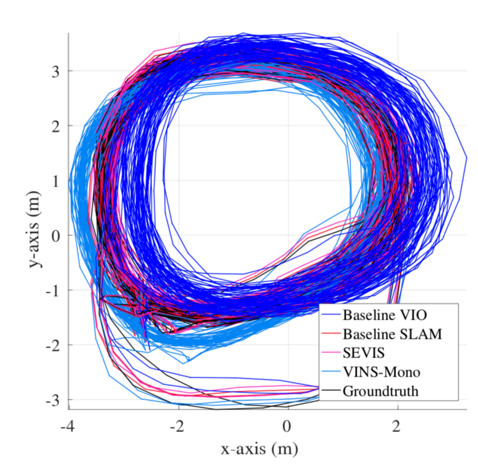
2. Single-IMU/camera VINS

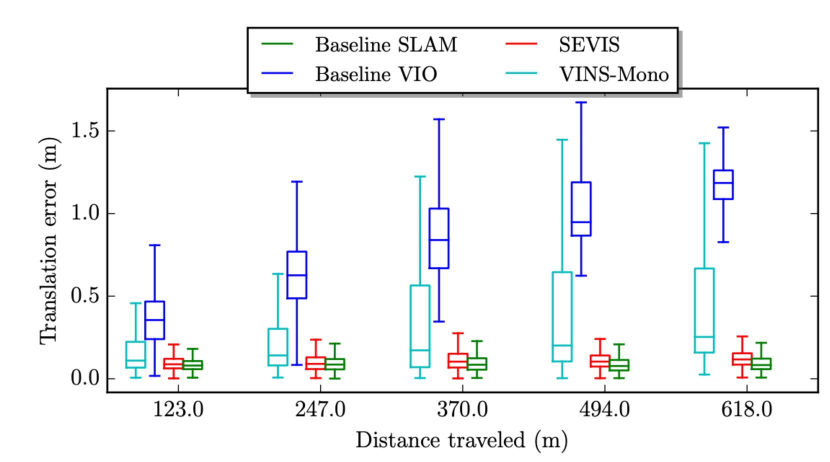
- **Schmidt-MSCKF w/ loop closures** [ICRA 2019a]



  - ❑ Exploit Schmidt-KF for real-time **consistent** inclusion of old keyframes by only updating their cross-correlations
  - ❑ Leverage MSCKF nullspace-based marginalization, allowing for **efficient** processing measurements of keyframe-based loop-closures

- **Schmidt-EKF visual-inertial SLAM** [CVPR 2019]





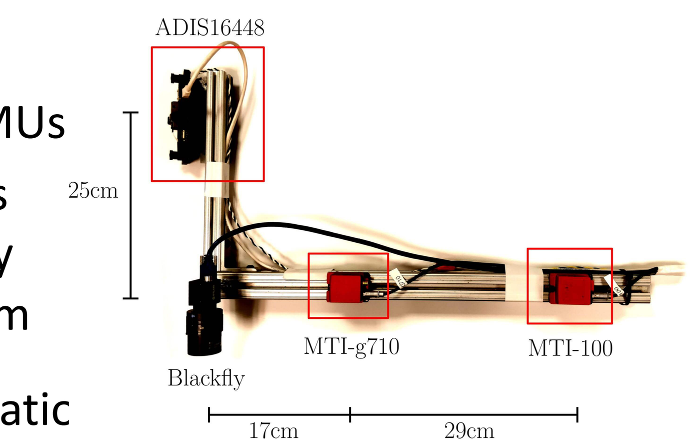
  - ❑ Adapt the Schmidt-KF formulation to selectively include informative features in the state vector while treating them as nuisance parameters once matured

3. Multi-IMU multi-camera (MIMC)-VINS

- **Multi-cam VIO** [ICRA 2019b]
  - ❑ Versatile MSCKF-based VIO using arbitrary number of asynchronous cameras
  - ❑ Perform online calibration of both IMU-camera spatial/temporal extrinsics and camera intrinsics

Number of Cameras	Outdoor	Tum	Gore	Average
1	0.393 / 1.208	0.596 / 0.349	0.993 / 0.442	0.661 / 0.666
2	0.287 / 0.892	0.552 / 0.242	0.532 / 0.231	0.457 / 0.455
3	0.260 / 0.784	0.422 / 0.211	0.363 / 0.206	0.348 / 0.400
4	0.229 / 0.661	0.294 / 0.162	0.350 / 0.192	0.291 / 0.339
5	0.221 / 0.647	**0.267** / 0.153	0.365 / 0.180	0.284 / 0.327
6	**0.217** / **0.606**	0.279 / **0.151**	**0.337** / **0.171**	**0.278** / **0.309**

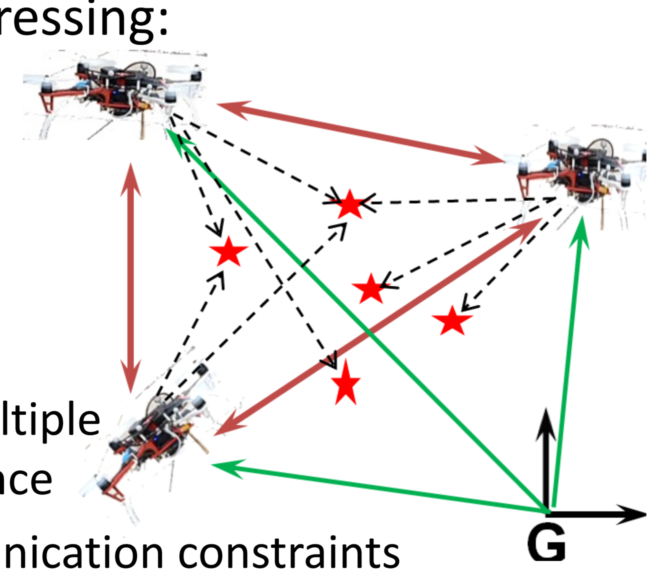
- **Multi-IMU VIO** [ICRA 2019c]
  - ❑ Resilient VIO utilizing an arbitrary number of IMUs
  - ❑ Jointly propagate all IMUs while enforcing rigid-body hard constraints btw. them
  - ❑ Provide continuous estimatic failures of individual IMUs



Number of IMU	Outdoor	Tum	Gore	Average
1	1.462 / 4.377	0.836 / 0.699	1.869 / 1.915	1.389 / 2.330
2	1.095 / 3.325	0.850 / 0.654	1.830 / 1.564	1.258 / 1.848
3	0.904 / 2.867	0.859 / 0.563	1.704 / 1.344	1.156 / 1.591
4	0.799 / 2.555	0.819 / 0.528	**1.574** / 1.232	1.064 / 1.438
5	0.696 / 2.299	0.766 / 0.503	1.642 / 1.088	1.035 / 1.296
6	**0.645** / **2.176**	**0.739** / **0.468**	1.584 / **1.016**	**0.989** / **1.220**

4. Cooperative MIMC-VINS

- To perform consistent cooperative visual-inertial estimation under resource constraints while addressing:
  - ❑ Distributed estimation w/ relative measurements to other vehicles
  - ❑ Asynchronous clocks on different UAVs and time-varying spatial and temporal calibration
  - ❑ Robust, efficient initialization of multiple UAVs to a common frame of reference
  - ❑ Efficient data sharing under communication constraints



5. Technical approach and innovations

- Resource-adaptive consistent visual-inertial estimation as constrained optimization to optimally utilize resources

- Leverage deep learning/AI to design visual-and-inertial 3D perception to semantically & spatially understand scenes
- Develop formal tools for characterization and co-design of UAV hardware and software systems

6. Broader impact

- Offer great social benefits by enabling UAVs to work in human non-accessible or unspecified environments
- Foster innovative applications in robotics such as aerial transportation during humanitarian aid and disaster relief, thus boosting economic development
- Promote hands-on learning in undergraduate education and enrich graduate curriculum, and create opportunities for students to perform meaningful robotics research

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