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Navion: A Fully Integrated Energy-Efficient Visual-Inertial Odometry Accelerator for Autonomous Navigation of Nano Drones

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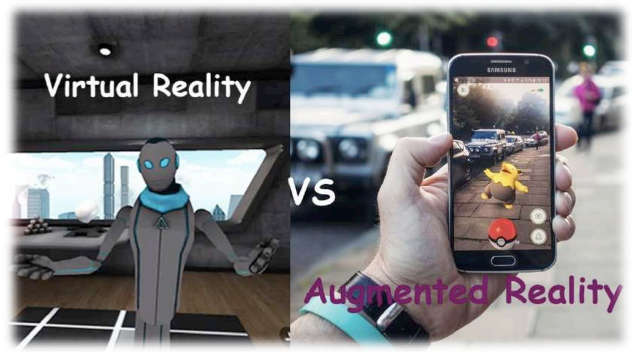
Motivation

Autonomous navigation of ***nano drones***

Virtual and augmented reality on ***energy-constrained devices***

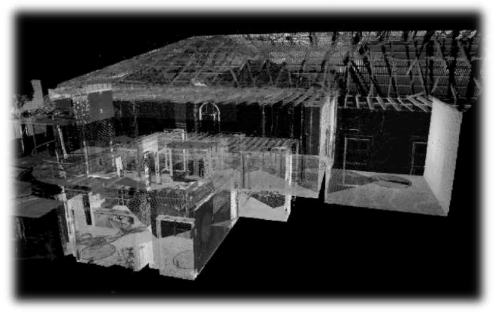


No GPS

Use images and inertial data for ***state estimation***

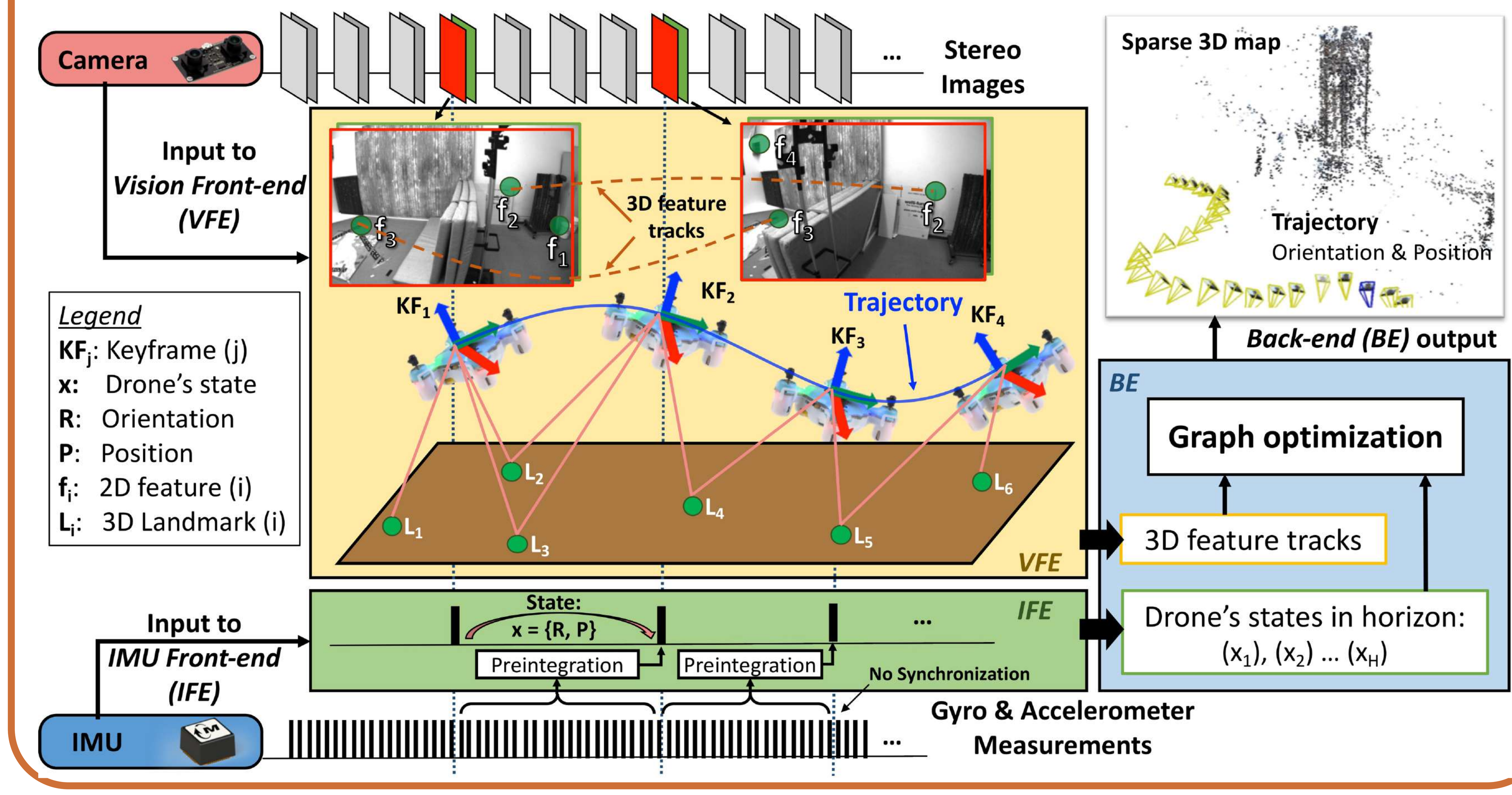
Location (Trajectory)

3D Map



VIO: Visual-Inertial Odometry

VIO is a special instance of Simultaneous Localization and Mapping (SLAM)



Vision Frontend (VFE)

Feature Detection (Identify features)

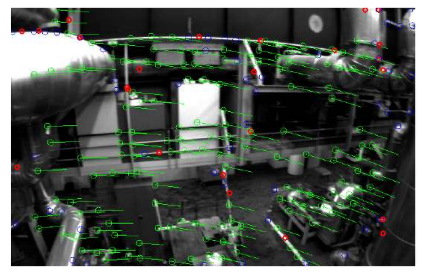
- Extract Harris corners (up to 200 per frame)
- Search and distribute across the whole frame
- Compute for every keyframe

3D Stereo (Estimate depth of features – *a.k.a. landmarks*)

- Sparse block matching
- Compute for every keyframe

Feature Tracking (Estimate movement of features)

- Lucas-Kanade pyramidal optical flow
- Supports up to 3 pyramid levels
- Compute for all frames (measure movement between keyframes)

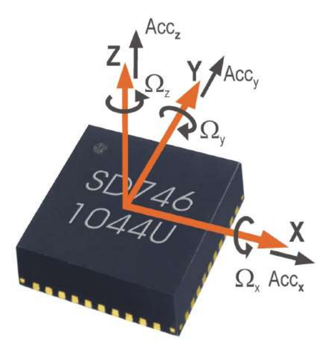


IMU Frontend (IFE)

Gyroscope: Estimate Rotation

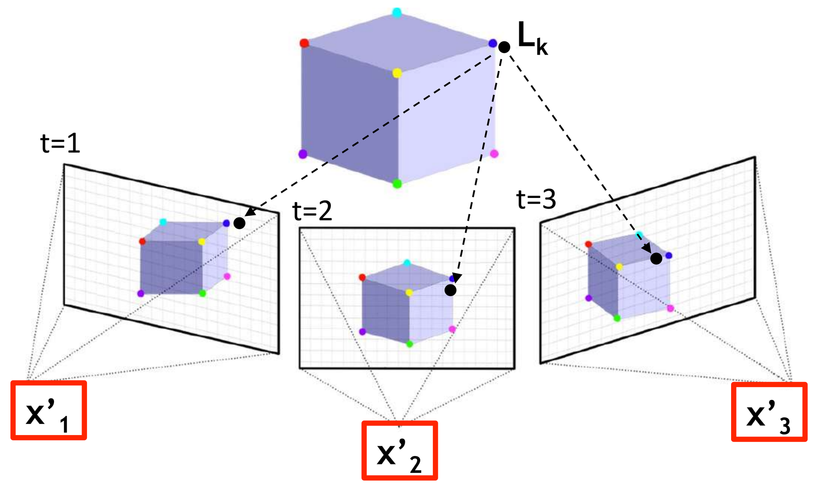
Accelerometer: Estimate Translation

Pre-integration: Integrate IMU measurements into one per keyframe [1]



Backend (BE)

Minimize inconsistencies between measurements across time

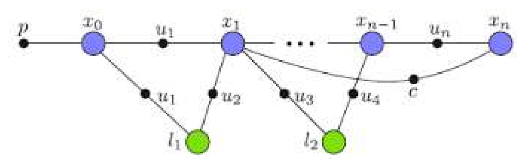


Update state estimates (x')

Fuses vision and IMU estimates to refine the final state estimates (x')

$$\min_{x} \sum_{(i,j)\in\mathcal{F}} \|r_{\mathrm{IMU}}(x, \Delta\tilde{R}_{ij}, \Delta\tilde{p}_{ij}, \Delta\tilde{v}_{ij})\|^2 + \sum_{k\in\mathcal{L}} \sum_{i\in\mathcal{F}_k} \|r_{\mathrm{CAM}}(x, l_k, u^l_{ik}, u^r_{ik})\|^2 + \|r_{\mathrm{PRIOR}}(x)\|^2$$

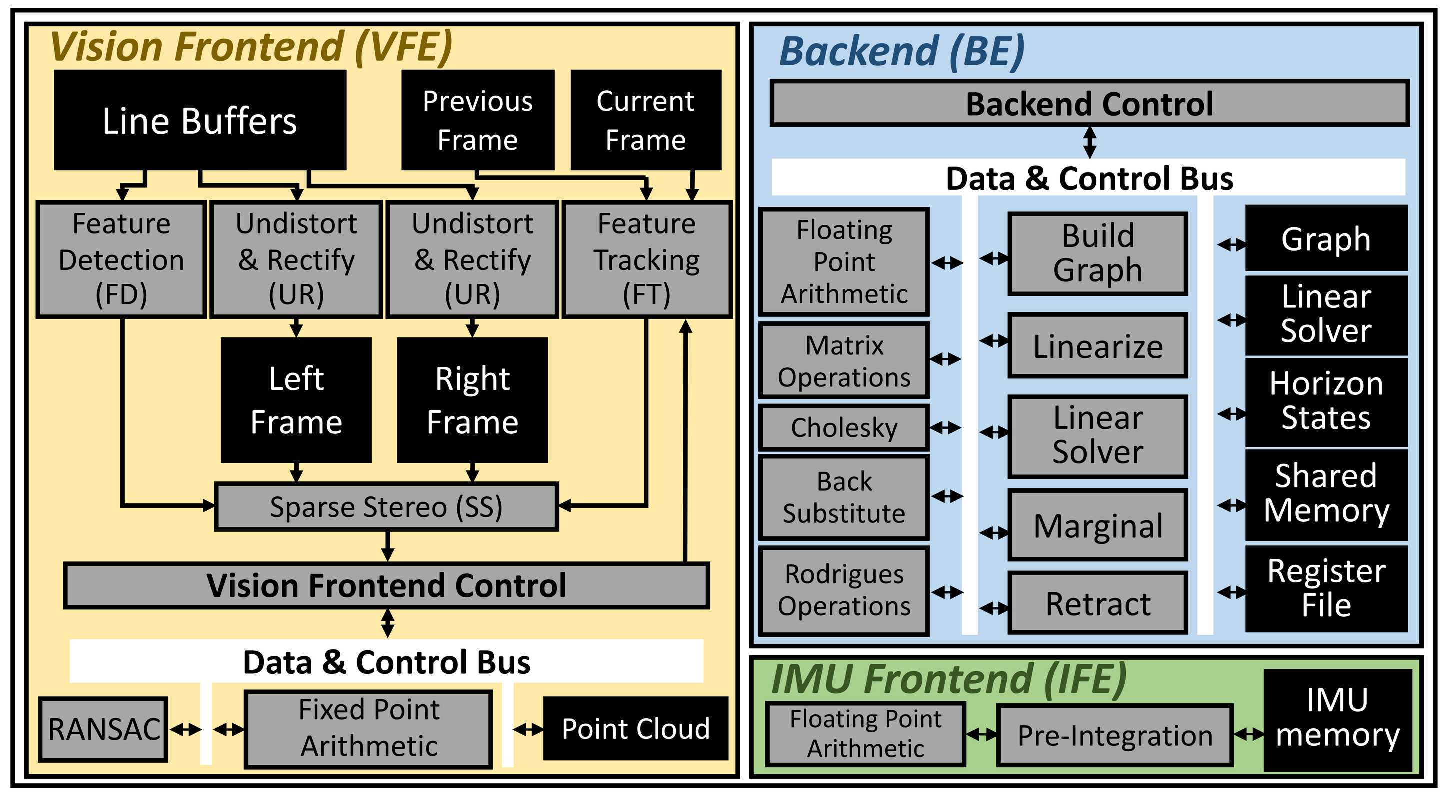
IMU Factors   Vision Factors



Over 4000+ factors in optimization

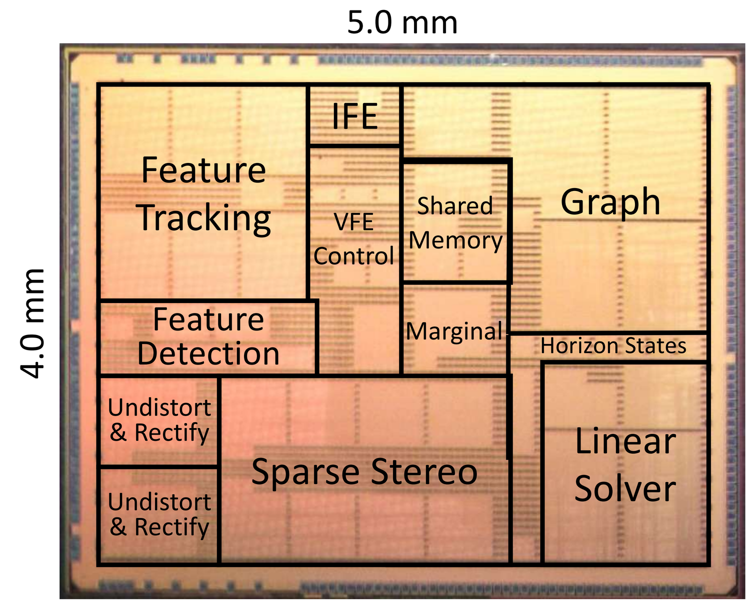
Solve with state-of-the-art factor graph algorithm

Navion Chip Architecture



Fully Integrated System (no off-chip processing or storage)

Navion Results



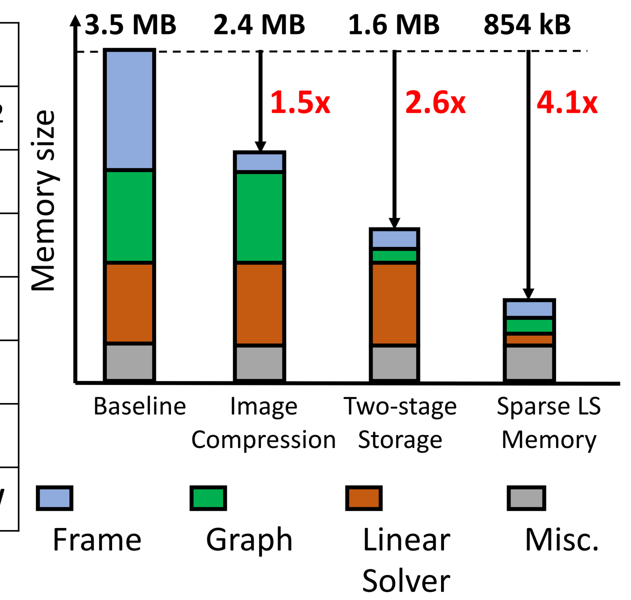
Key Challenges

- Large frame memories for feature tracking and stereo computation
- Large graph memory with irregular memory access
- Slow linear solver

Our Approach

- Image compression
  - **4.4x** smaller frame memory
  - **4.9x** less power
- Sparse feature tracks data structure
  - **5.4x** smaller graph memory
- Sparse linear solver
  - **5.2x** smaller linear solver memory
  - **7.2x** speed up

Technology	65nm CMOS
Chip area	4.0 x 5.0 mm²
Logic gates	2,043 kgates
SRAM	854 KB
Frame size	480x752
Camera	28 – 171 fps
Keyframe	16 – 90 fps
Power	27 – 43.2 mW



Platform	Xeon [2]	ARM [2]	FPGA [2]	ASIC (This work)
Accuracy*	0.20%	0.20%	0.24%	0.28%
Camera max fps	21	5	20	171
Keyframe max fps	13	3	5	90
Power (W)	26.10	2.33	1.46	0.024

*Measured on EuRoc MAV dataset

Sponsors

AFOSR · NSF

Want to know more?

Visit navion.mit.edu

References

[1] C. Forster, L. Carlone, F. Dellaert, D. Scaramuzza. "On-manifold preintegration theory for fast and accurate visual-inertial navigation," IEEE Trans. Robotics, 2016

[2] Z. Zhang, A. Suleiman, L. Carlone, V. Sze, S. Karaman, "Visual-Inertial Odometry on Chip: An Algorithm-and-Hardware Co-design Approach," RSS 2017.