iCalib: Inertial Aided Multi-Sensor Calibration

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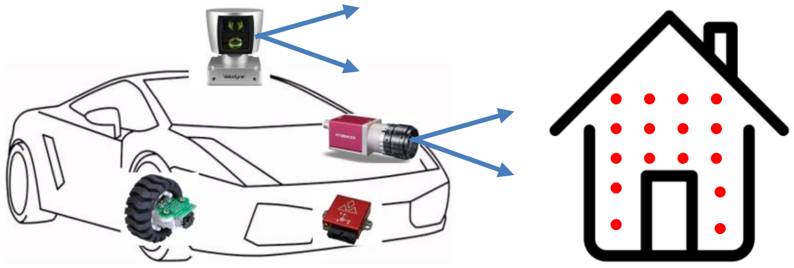
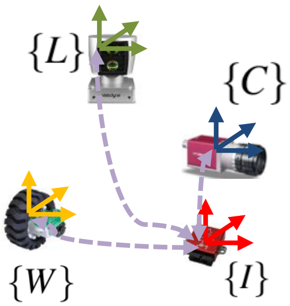
Introduction

- Autonomous robots are equipped with multi-heterogeneous sensors.
  - **IMU, Camera, LiDAR, Wheel encoder**
- Multi-sensors can provide more comprehensive perception capabilities.
  - High frequency pose estimation from IMU and wheel encoder
  - Texture rich images from cameras, sparse point clouds from LiDAR
- Spatial-temporal calibration are essential for multi-modal perception.

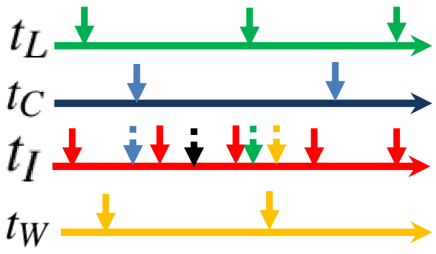
Multi-Sensor Perception



Spatial Calibration



Temporal Calibration



Related works

Algorithm	IMU	Camera	LiDAR	Wheel	t_{off}	Target
Kalibr [Furgale2013]	×	×			×	×
CamOdoCal [Heng2013]		×		×		×
MSG-CAL [Owens2015]		×	×			×
LI-Calib [Lv2020]	×		×			
MIMC [Eckenhoff2020]	×	×			×	
LIC-fusion [Zuo2020]	×	×	×		×	
VIWO [Lee2020]	×	×		×	×	
iCalib (Proposed)	×	×	×	×	×	×

- Only IMU-Cam calib

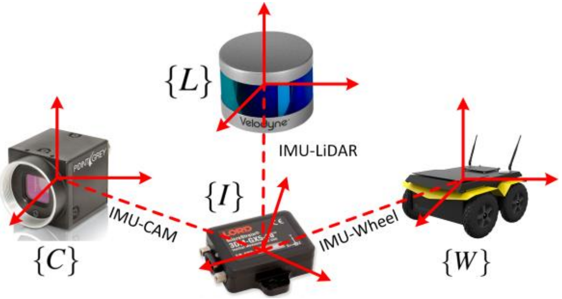
- Optimization based
- For sensor pair
- No time offset calib

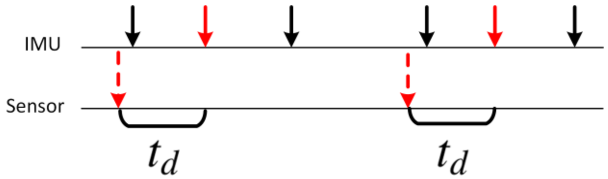
- Filter based
- Online calib for pose

- iCalib can calibrate all spatial-temporal params for all sensors.

Contributions

- iCalib: an inertial aided multi-sensor calibration system
  - Asynchronous IMU, multi-cameras, LiDAR and wheel encoder.
  - Degenerate motion identification for multi-sensor calibration

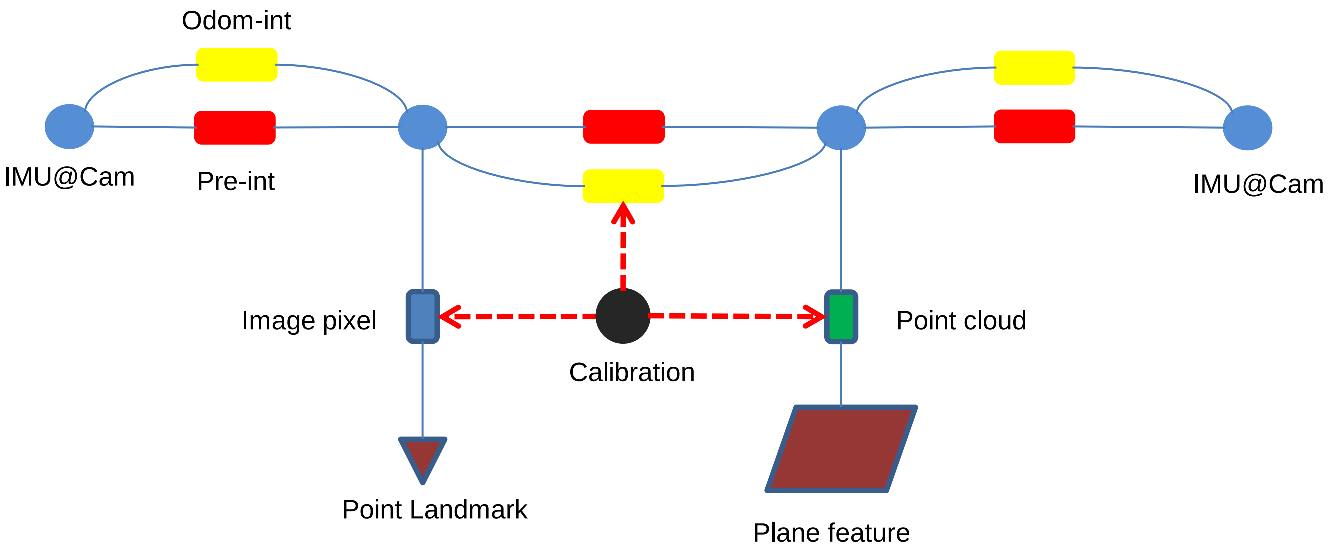




- Kinematics or bounding poses interpolation to fuse sensor measurements.
  - Camera pixels, LiDAR plane point clouds, 2D wheel integration

Optimization Graph

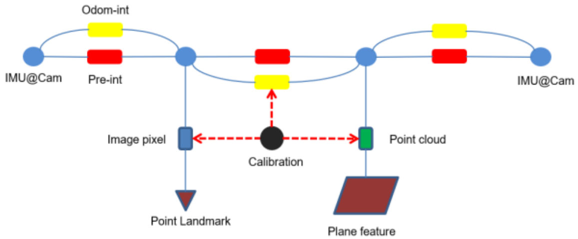
- Inertial information to build the pose backbone for the graph.
  - Integrate base IMU at CAM frequency for base VI graph.
  - Additional cameras and LiDAR measures added to base VI graph.
  - Calibration are added when each edge is inserted.



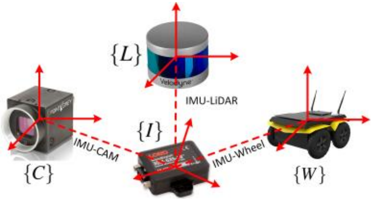
State Vector

- Historical IMU poses, features and calibration:

$$\mathbf{x} = \begin{bmatrix} \underbrace{\mathbf{x}_{I_0}^\top \quad \dots \quad \mathbf{x}_{I_k}^\top}_{\text{IMU}} & \underset{\text{Feature}}{\mathbf{x}_F^\top} & \underset{\text{Calib}}{\mathbf{x}_{calib}^\top} \end{bmatrix}^\top$$

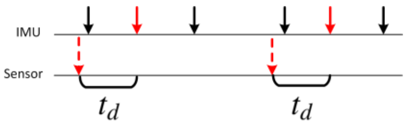


  - IMU state: $$\mathbf{x}_{I_k} = \begin{bmatrix} {}^{G}_{I_k}\bar{q}^\top & {}^{G}\mathbf{p}_{I_k}^\top & {}^{G}\mathbf{v}_{I_k}^\top & \mathbf{b}_{\omega_k}^\top & \mathbf{b}_{a_k}^\top \end{bmatrix}^\top$$



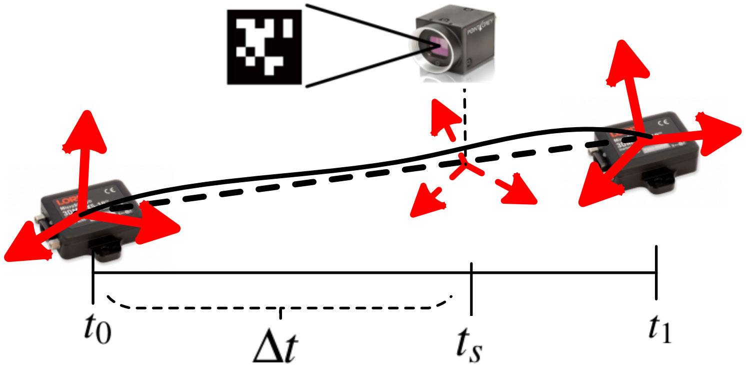
  - Feature: $$\mathbf{x}_F = \begin{bmatrix} \underbrace{{}^{G}\mathbf{p}_{f_1}^\top \quad \dots \quad {}^{G}\mathbf{p}_{f_m}^\top}_{\text{Points}} & \underbrace{{}^{G}\mathbf{p}_{\pi_1}^\top \quad \dots \quad {}^{G}\mathbf{p}_{\pi_l}^\top}_{\text{Planes}} \end{bmatrix}^\top$$

  - Calib state: $$\mathbf{x}_{calib} = \begin{bmatrix} \underbrace{\mathbf{x}_{CI_1}^\top \quad \dots \quad \mathbf{x}_{CI_s}^\top}_{\text{Cam}} & \underset{\text{LiDAR}}{\mathbf{x}_{LI}^\top} & \underset{\text{Wheel}}{\mathbf{x}_{WI}^\top} \end{bmatrix}^\top$$



Handle Asynchronous Sensors

- Why interpolation?
  - Fuse asynchronous measures
  - Approximation in small interval
  - Linear model with constant velocity



$$\Delta t = t_s + t_d - t_0$$

Rotation: $${}^{G}_{I_s}\mathbf{R} = {}^{G}_{I_0}\mathbf{R}\ \mathrm{Exp}(\boxed{\boldsymbol{\omega}} \cdot \Delta t)$$

Position: $${}^{G}\mathbf{p}_{I_s} = {}^{G}\mathbf{p}_{I_0} + \boxed{\mathbf{v}} \cdot \Delta t$$

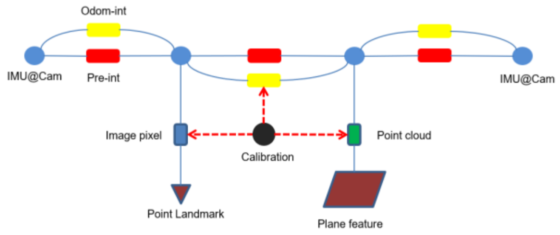
- How to define constant velocity?
  - Bounding pose based interpolation
  - Kinematics based interpolation

$$\boldsymbol{\omega} = \frac{\mathbf{Log}({}^{G}_{I_0}\mathbf{R}^{\top}\,{}^{G}_{I_1}\mathbf{R})}{t_1 - t_0} \qquad \mathbf{v} = \frac{{}^{G}\mathbf{p}_{I_1} - {}^{G}\mathbf{p}_{I_0}}{t_1 - t_0}$$

$$\boldsymbol{\omega} = {}^{I_0}\boldsymbol{\omega} \qquad \mathbf{v} = {}^{I_0}\mathbf{v}$$

- Optimize the state with sensor costs:

$$\min_{\mathbf{x}} \sum \mathbb{C}_I + \sum \mathbb{C}_C + \sum \mathbb{C}_L + \sum \mathbb{C}_W$$



- IMU: pre-integration cost based on **ACI²**[Yang2020ICRA]:

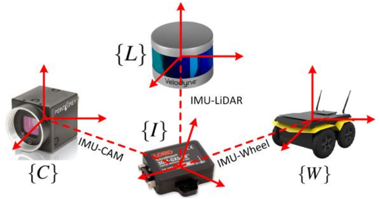
$$\mathbb{C}_{I_{k+1}} \triangleq \|\mathbf{z}_{I_{k+1}} - \mathbf{h}_I(\mathbf{x}_{I_k}, \mathbf{x}_{k+1})\|^2_{\mathbf{Q}^{-1}_{I_{k+1}}}$$

- CAM: image projection cost[Geneva2020ICRA]:

$$\mathbb{C}_C \triangleq \|\mathbf{z}_C - \mathbf{h}_C({}^G_{I_{in}}\mathbf{R}, {}^G\mathbf{p}_{I_{in}}, \mathbf{x}_{CI}, {}^G\mathbf{p}_f)\|^2_{\mathbf{Q}_C^{-1}}$$

- LiDAR: point-to-plane cost from **LIC-Fusion 2.0**[Zuo2020IROS]:

$$\mathbb{C}_L \triangleq \|\mathbf{z}_L - \mathbf{h}_L({}^G_{I_{in}}\mathbf{R}, {}^G\mathbf{p}_{I_{in}}, \mathbf{x}_{LI}, {}^G\mathbf{p}_\pi, \mathbf{0})\|^2_{\mathbf{Q}_L^{-1}}$$

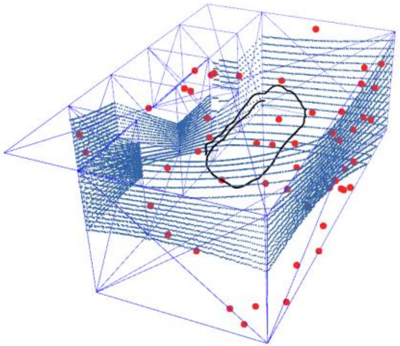


- Wheel : 2D odometer integration cost from **VIWO**[Lee2020IROS]:

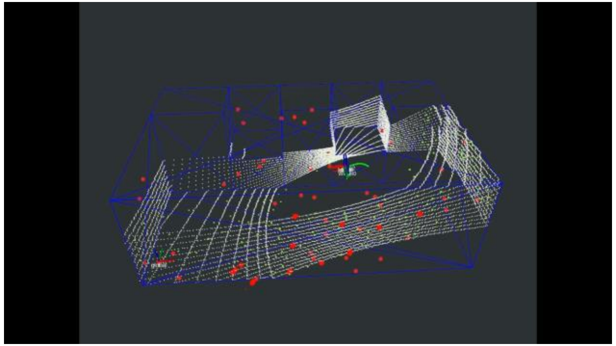
$$\mathbb{C}_W \triangleq \|\mathbf{z}_W - \mathbf{h}_W(\mathbf{x}_{I_{in,k}}, \mathbf{x}_{I_{in,k+1}}, \mathbf{x}_{WI})\|^2_{\mathbf{Q}_W^{-1}}$$

Simulation - Setup

- 1 IMU + 3 CAM + 1 LiDAR + 1 Wheel encoder
- Structural environment
- 3D motion and 2D planar motion
- All spatial-temporal calibration
- All camera intrinsic parameters

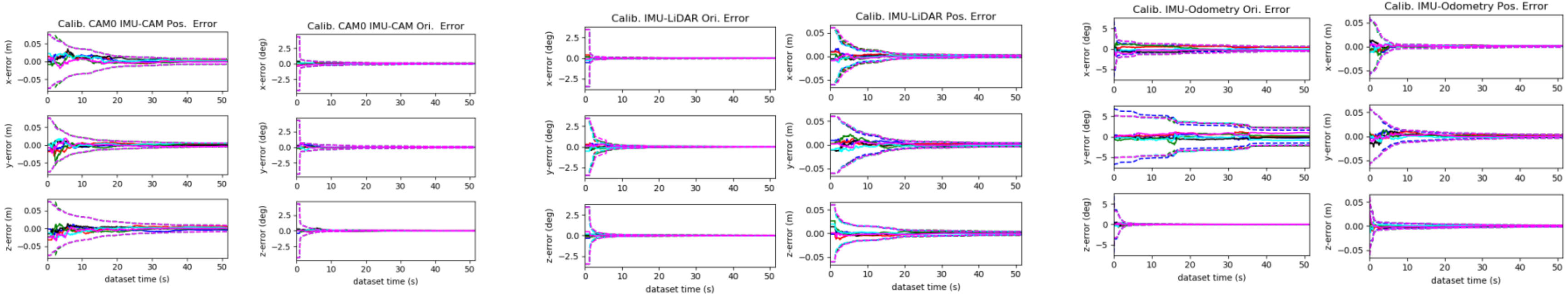


Parameter	Value	Parameter	Value
IMU Freq. (hz)	300	Max Cam Pts	100
Cam Freq. (hz)	20/10/10	Cam Time offset (ms)	10/-10/0
LiDAR Freq. (hz)	8	LiDAR Time offset (ms)	-10
Wheel Freq. (hz)	70	Wheel Time offset (ms)	0
LiDAR Rings	16	LiDAR Range Noise (m)	0.03
Pixel Proj. (px)	1	Wheel. White Noise	0.03



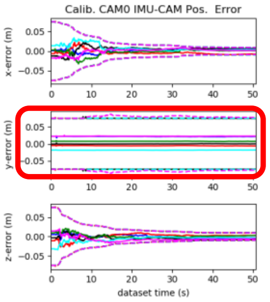
Simulation - Results

- 3D motion: all calibration converge nicely!

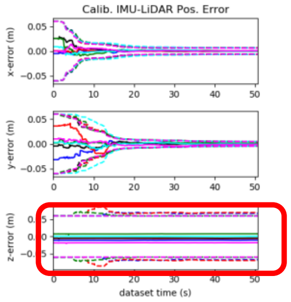


- 2D planar motion is degenerate for calibration!

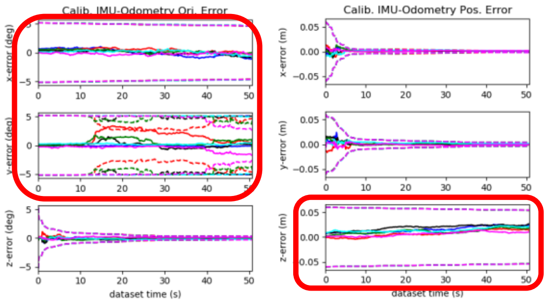
IMU-CAM Translation



IMU-LiDAR Translation

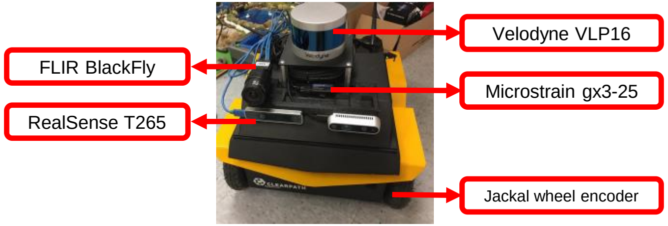


IMU-Wheel

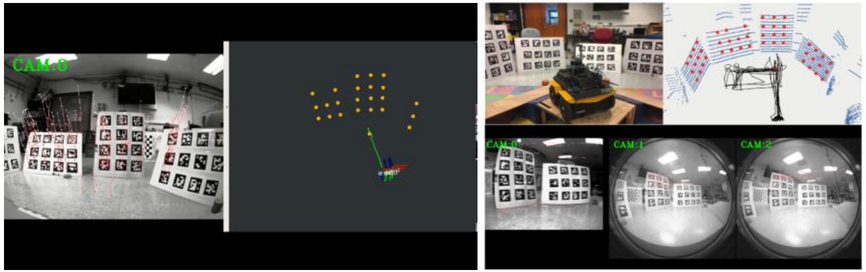


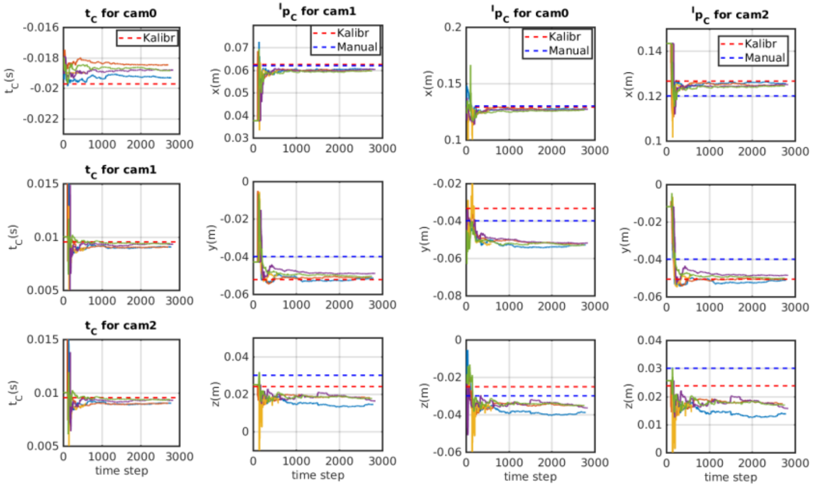
Real World Experiments

- 3 sets of experiments with Jackal
  - 1 IMU + 3 cams
  - 1 IMU + 1 cam + 1 LiDAR
  - 1 IMU + 1 cam + 1 wheel

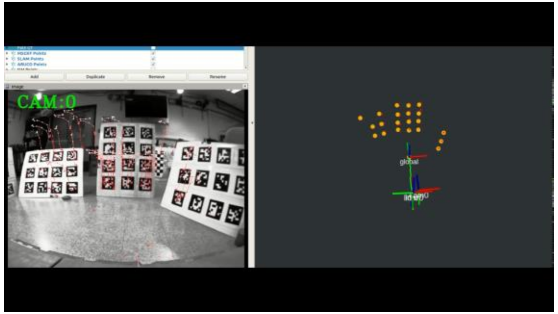


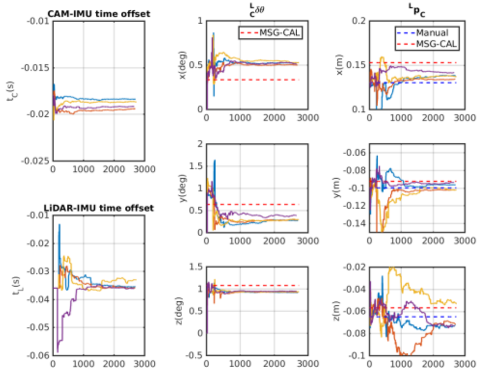
- IMU + 3 cameras
  - Kalibr results as for comparison
  - 4 datasets are tested!
  - Spatial-temporal converges!



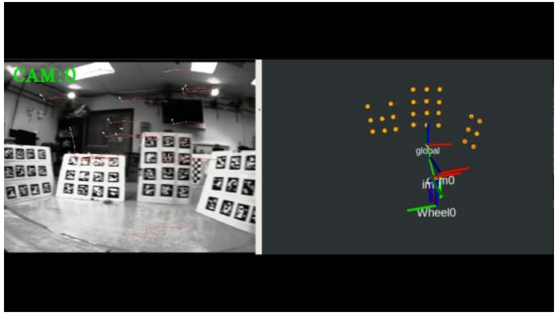


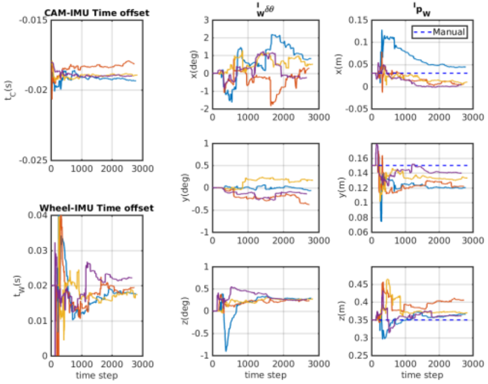
- IMU + CAM + LiDAR
  - 4 datasets are tested
  - MSG-CAL for comparison
  - IMU-LiDAR converges





- IMU + CAM + Wheel
  - 4 datasets are tested
  - IMU-Wheel converges slower
  - Improvement is needed.



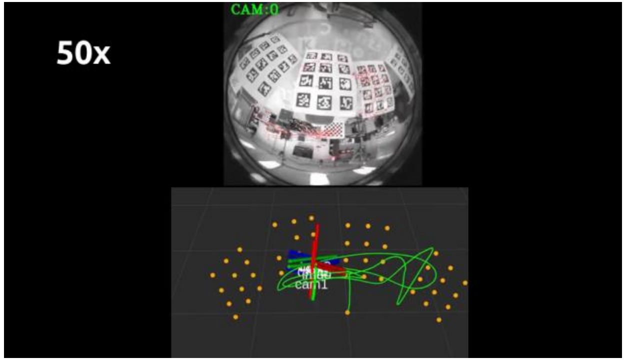


Calibration under constrained motion should be improved!

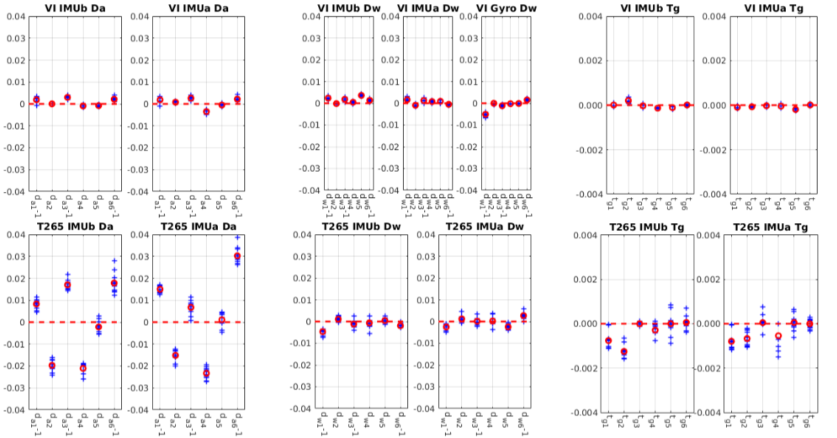
Latest Breakthrough Results

- Multi-visual-inertial calibration **(MVIS)**
  - Multi-asynchronous IMUs
  - All IMU spatial-temporal and intrinsics calibrated
  - Degenerate motions identified

Sensor	Extrinsics	Temporal	Intrinsics	Qty
Base IMU	–	–	X	1
Aux IMU	X	X	X	≥ 1
Aux Gyro	X	X	X	≥ 1
Camera	X	X	X	≥ 1



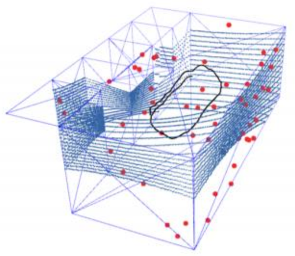
Acc. Calib **Gyro Calib** **Gravity Sensitivity**

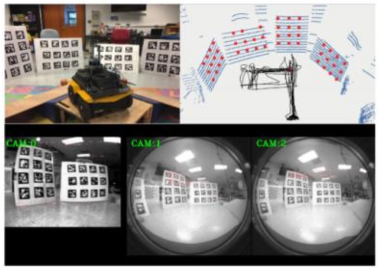


Microstrain > RealSense!

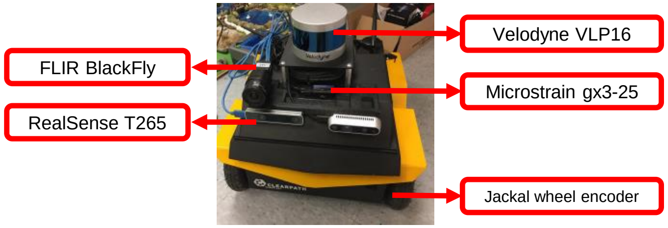
Gravity sensitivity is marginal!

- Summary
  - iCalib: multi-sensor calibration
  - Degenerate motion analysis
  - Extensive simulations to verify consistency
  - Real world experiments on ground vehicles





Sensor	Spatial	Temporal	Intrinsic	Qty.	Status
Base IMU	-	-	X	1	Done
Aux IMU	X	X	X	≥ 1	Done
Aux Gyro	X	X	X	≥ 1	Done
Camera	X	X	X	≥ 1	Done
LiDAR	X	X	-	1	Done
Wheel	X	X	-	1	To improve



- Future Works
  - Calibration under constrained motions
  - Improve the wheel calibration
  - Continuous time formulation

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