Online IMU Intrinsic Calibration: Is It Necessary?

Yulin Yang[1], Patrick Geneva[1] , Xingxing Zuo[2], Guoquan (Paul) Huang[1]

[1] Robot Perception and Navigation Group (RPNG), University of Delaware

[2] Institute of Cyber-System and Control, Zhejiang University, Hangzhou, China

Motivation

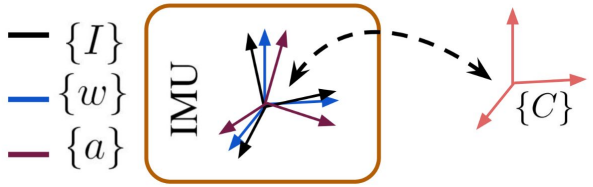
- Visual-Inertial Navigation System (VINS) has been widely used in **6D pose tracking** for mobile robots
- Online calibration can benefit system performance.
  - Camera extrinsics, intrinsics, and cam-imu time offset
  - Limited investigation of **IMU intrinsics**
- Does online IMU intrinsic calibration improve performance?
  - IMU intrinsic **observability**?
  - Any **degenerate** motions?

IMU Intrinsic Model

- The corrected IMU readings can be listed as:

$$^{I}\boldsymbol{\omega} = {}^{I}_{w}\mathbf{R}\mathbf{D}_w\left({}^{w}\boldsymbol{\omega}_m - \mathbf{b}_g - \mathbf{n}_g\right)$$

$$^{I}\mathbf{a} = {}^{I}_{a}\mathbf{R}\mathbf{D}_a\left({}^{a}\mathbf{a}_m - \mathbf{b}_a - \mathbf{n}_a\right) - {}^{I}_{G}\mathbf{R}\,{}^{G}\mathbf{g}$$



where $\mathbf{D}_*$ represents scale and skew correction to {w} or {a}

- 4 IMU model variants (15 DoF):
  - imu1 $\mathbf{D}_{a6}$ $\mathbf{D}_{w6}$ ${}^{I}_{w}\mathbf{R}$
  - imu3 $\mathbf{D}_{a6}$ $\mathbf{D}_{w9}$
  - imu2* $\mathbf{D}_{w6}$ $\mathbf{D}_{a6}$ ${}^{I}_{a}\mathbf{R}$
  - imu4 $\mathbf{D}_{w6}$ $\mathbf{D}_{a9}$

$$\mathbf{D}_{*6} = \begin{bmatrix} d_{*11} & d_{*12} & d_{*13} \\ 0 & d_{*22} & d_{*23} \\ 0 & 0 & d_{*33} \end{bmatrix}$$

skewness

scaleness

- System State (including IMU, intrinsics and feature): $\mathbf{x} = \begin{bmatrix} \mathbf{x}_I^\top & \mathbf{x}_{in}^\top & \mathbf{x}_f^\top \end{bmatrix}^\top$
- System ODE: $\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{n}_I)$ → $\tilde{\mathbf{x}}_{k+1} \simeq \boldsymbol{\Phi}_{(k+1,k)}\tilde{\mathbf{x}}_k + \mathbf{G}_k\mathbf{n}_{Ik}$
- Visual Feats: $\mathbf{z} \triangleq \begin{bmatrix} u \\ v \end{bmatrix} = \mathbf{h}(\mathbf{x}) + \mathbf{n}_f$ → $\tilde{\mathbf{z}}_k \simeq \mathbf{H}_k\tilde{\mathbf{x}}_k + \mathbf{n}_{fk}$

*** imu2 is used for the rest of the paper.**

Observability Analysis

- The observability matrix can be built:

$$\mathbf{M} = \begin{bmatrix} \mathbf{M}_1 \\ \mathbf{M}_2 \\ \vdots \\ \mathbf{M}_k \end{bmatrix} = \begin{bmatrix} \mathbf{H}_1 \\ \mathbf{H}_2\mathbf{\Phi}_{(2,1)} \\ \vdots \\ \mathbf{H}_k\mathbf{\Phi}_{(k,1)} \end{bmatrix}$$

★ **Given fully-excited motions, even with monocular camera, IMU intrinsic parameters will be observable.**

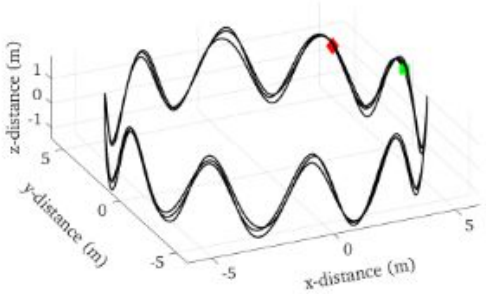
- Degenerate motions

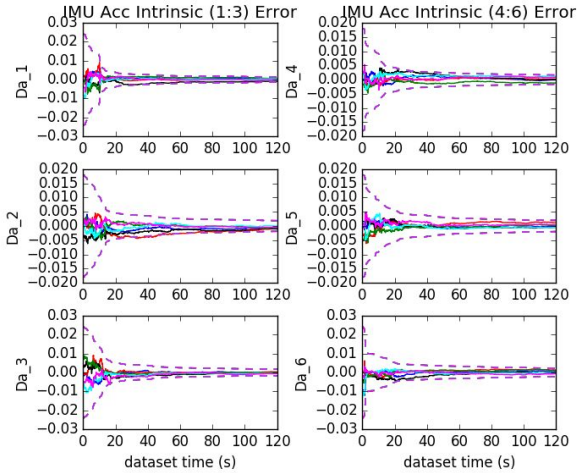
Motion Types	Nullspace Dim.	Unobservable Parameters
constant ${}^{w}\omega_1$	1	d_{w11}
constant ${}^{w}\omega_2$	2	d_{w12}, d_{w22}
constant ${}^{w}\omega_3$	3	$d_{w13}, d_{w23}, d_{w33}$
constant ${}^{a}a_1$	3	d_{a11}, pitch and yaw of ${}^{I}_{a}\mathbf{R}$
constant ${}^{a}a_2$	3	d_{a12}, d_{a22}, roll of ${}^{I}_{a}\mathbf{R}$
constant ${}^{a}a_3$	3	$d_{a13}, d_{a23}, d_{a33}$

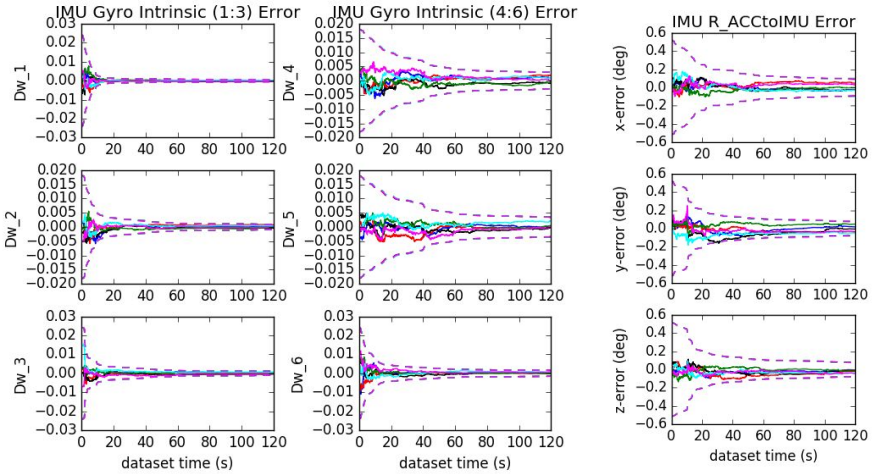
★ **Any combination of these degenerate motions is still degenerate.**
- **1-axis rotation (e.g. MAVs)**
- **Constant accel x motion (e.g. cars)**
- **Planar motion (e.g. cars)**

Simulation: General Motion

- Simulation Setup
  - OpenVINS simulator with IMU-camera pair
  - 4 variants are tested with Monte-Carlo
  - 216 meter with 3 motion profiles
- Fully-excited motion, full calibration, **all converge !**



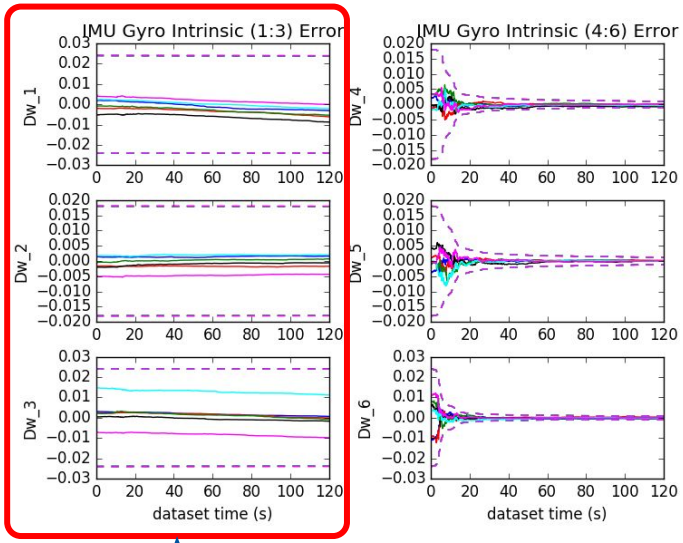




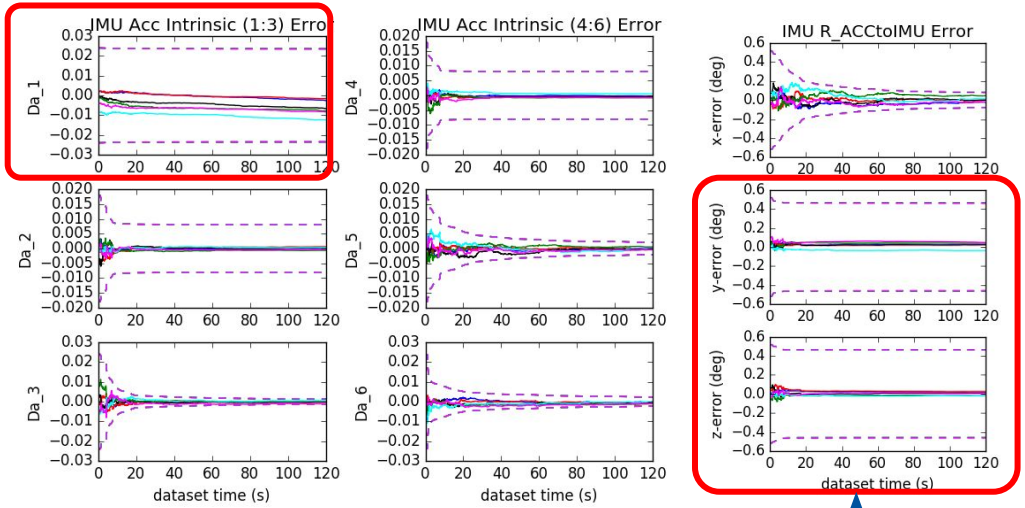
All 3 sigma bounds and errors decrease towards zero!

Simulation: Degenerate Motions

- 1-axis rotation: dw1, dw2, dw3
- Constant a_x: da1, pitch and yaw of ${}^{I}_{a}\mathbf{R}$



Parameters fail to converge and gain information



Parameters fail to converge and gain information

Real-World: TUM and KAIST

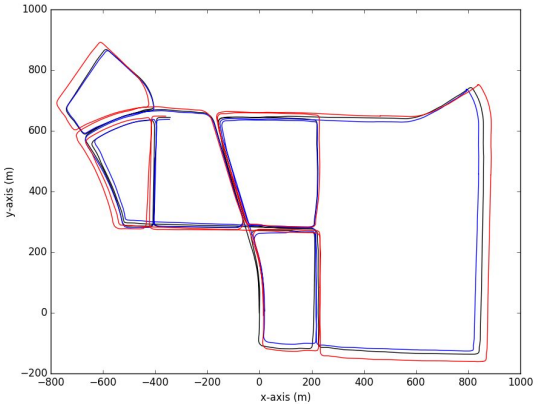
TUM VI (handheld)

TABLE IV: Absolute Trajectory Error (ATE) on TUM VI room equences (with units degrees/meters). *imu1* denotes $\mathbf{D}_{a6}, \mathbf{D}_{\omega 6}, {}^{I}_{w}\mathbf{R}$; *imu2* denotes $\mathbf{D}_{a6}, \mathbf{D}_{\omega 6}, {}^{I}_{a}\mathbf{R}$; *imu3* denotes $\mathbf{D}_{a6}, \mathbf{D}_{\omega 9}$; *imu4* denotes $\mathbf{D}_{a9}, \mathbf{D}_{\omega 6}$.

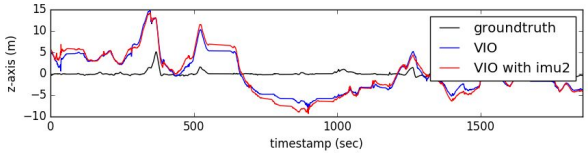
IMU Model	dataset-room1	dataset-room2	dataset-room3	dataset-room4	dataset-room5	dataset-room6	Average
VIO	1.430 / 0.089	1.173 / 0.064	1.934 / 0.088	1.333 / 0.054	1.140 / 0.092	0.888 / 0.056	1.317 / 0.074
imu1	0.954 / 0.066	1.153 / 0.059	1.809 / 0.074	1.175 / 0.038	1.028 / 0.073	1.017 / 0.033	1.189 / 0.057
imu2	0.877 / 0.077	1.170 / 0.051	1.974 / 0.076	1.148 / 0.039	0.950 / 0.081	0.825 / 0.038	1.157 / 0.060
imu3	0.957 / 0.065	1.142 / 0.058	1.836 / 0.075	1.211 / 0.039	1.006 / 0.073	1.021 / 0.034	1.196 / 0.057
imu4	0.893 / 0.077	1.173 / 0.052	1.896 / 0.076	1.134 / 0.038	1.259 / 0.097	0.823 / 0.038	1.196 / 0.063

Handheld Motions: Improved Accuracy!

KAIST (planar vehicle)



10km Urban 39 Trajectory



VIO RMSE: 1.5 deg 13.03 meters (0.12%)

VIO + IMU Calib: 1.41 deg 23.13 meters (0.22%)

Planar Motions: Hurts Performance!

Online IMU Intrinsic Calibration: Is It Necessary?

Recommended for <u>fully-excited</u> motions

Not recommended for underactuated motions (most non-handheld will be degenerate)

- Observability and degenerate motion analysis for IMU intrinsics
- Extensive evaluations in simulation and real-world
- Future: Full VINS calibration analysis

Yulin Yang

Yulin Yang, yuyang@udel.edu

Robot Perception and Navigation Group (RPNG)

RPNG