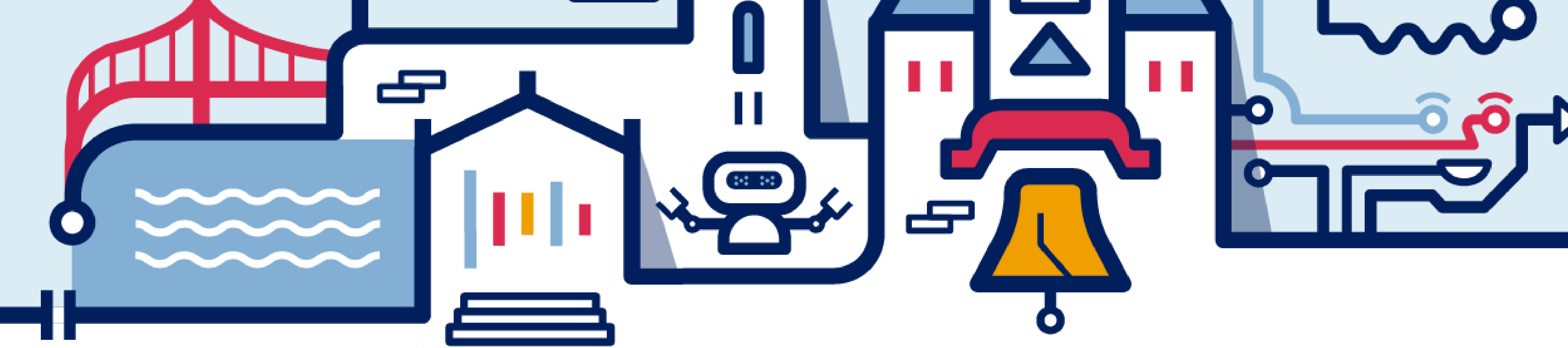

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Extrinsic Calibration of Multiple Inertial Sensors from Arbitrary Trajectories

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Why is Extrinsic Calibration of Multiple IMUs Necessary?

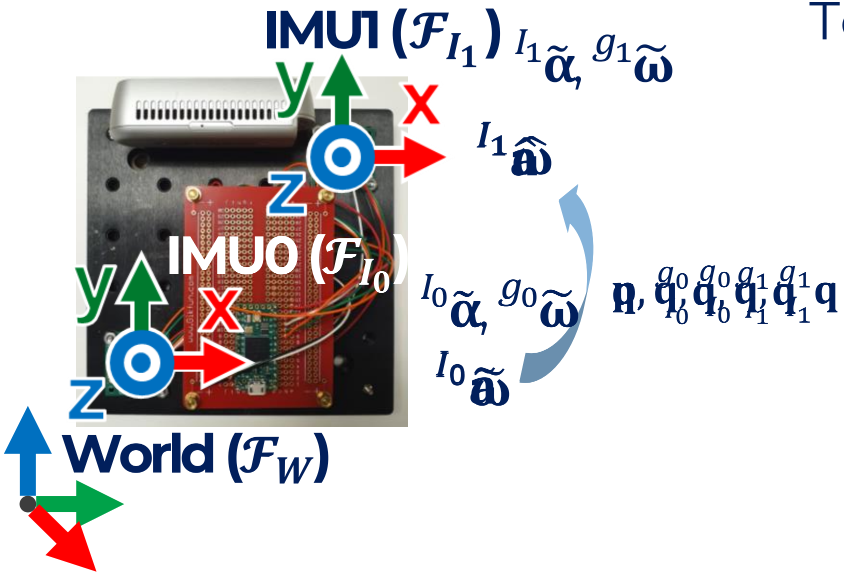
- Using multiple inertial measurement units (IMUs) has various applications:
  - Higher measurement accuracy
  - Increased bandwidth
  - Better fault tolerance
- It is essential to estimate the relative position and orientation (relative pose) of IMUs—so-called extrinsic calibration—before these applications

Our Contributions

- We especially focus on multi-IMU extrinsic calibration using neither instruments, aiding sensors, nor prescribed trajectory
- Existing approaches have limits:
  - Estimate only relative orientation, not position
  - Suitable for accelerometer-only arrays
  - Do not account for misalignment between accelerometer and gyroscope axes
- To address these issues, we solve a nonlinear least-squares problem penalizing the inconsistency between expected and actual IMU measurements

Solution Approach

- Imagine a two-IMU system for example…



To find: $\mathbf{p} \in \mathbb{R}^3$, $\mathbf{q} \in \mathbb{H}$, $^{g_0}_{I_0}\mathbf{q}$, $^{g_1}_{I_1}\mathbf{q} \in \mathbb{H}$

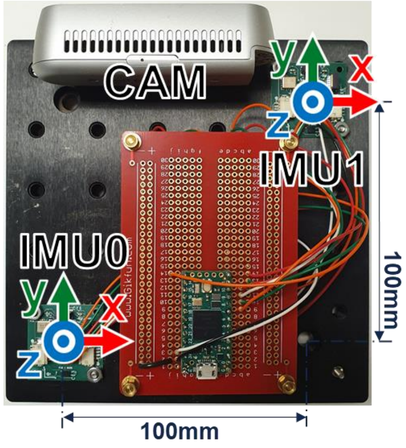
$$\mathbf{r}_a := {}^{I_1}\hat{\mathbf{a}} - {}^{I_1}\tilde{\mathbf{a}}$$

$$\mathbf{r}_g := {}^{g_1}\hat{\boldsymbol{\omega}} - {}^{g_1}\tilde{\boldsymbol{\omega}}$$

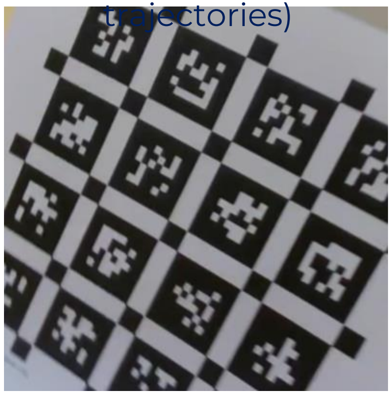
$$\min \sum \left(\|\mathbf{r}_a\|^2 + \|\mathbf{r}_g\|^2 \right)$$

Evaluation: Comparison to Kalibr

- Our method is compared to **Kalibr** over 65 trajectories lasting 60 seconds for each
- These trajectories were collected in three different conditions: *baseline*, *blurry*, *ill-lit*

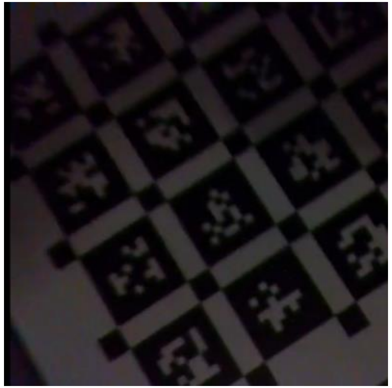


baseline (21 trajectories)



blurry (23 trajectories)

ill-lit (21 trajectories)



Averaged Results over 21 Trajectories in *Baseline* Condition

	Kalibr	Our Method
RMSE in $\mathbf{p}$ [mm]	4.39	1.64
RMSE in $\mathbf{q}$ [deg]	1.35	2.91
RMSE in ${}^{g}_{I}\mathbf{q}$ [deg]	2.06	2.50
computation time [ms]	106.96 ± 16.34	4.61 ± 0.36
success rate	19 / 21	21 / 21

$\mathbf{p}$: relative position, $\mathbf{q}$: relative orientation, ${}^{g}_{I}\mathbf{q}$: gyroscope misalignment

$\mathbf{p}_{\text{ref}}$: $[100, 100, 0] \pm [24.2, 24.2, 6.3]$ mm, $\mathbf{q}_{\text{ref}}$, ${}^{g}_{I}\mathbf{q}_{\text{ref}}$: $(\mathbf{e}, 0°) \pm (\mathbf{e}, 9.5°)$ for $\forall\, \mathbf{e} \in \mathbb{R}^3 \setminus \{\mathbf{0}\}$ (angle-axis)

- Our method shows comparable estimation to Kalibr with a shorter computation time

Averaged Results over 23 Trajectories in *Blurry* Condition

	Kalibr	Our Method
RMSE in p [mm]	70.41	2.02
RMSE in q [deg]	26.98	2.86
RMSE in ${}^{g}_{I}$q [deg]	30.67	2.05
computation time [ms]	98.99 ± 12.27	4.74 ± 0.58
success rate	14 / 23	23 / 23

$\mathbf{p}$: relative position, $\mathbf{q}$: relative orientation, ${}^{g}_{I}\mathbf{q}$: gyroscope misalignment

$\mathbf{p}_{\mathrm{ref}}$: $[100, 100, 0] \pm [24.2, 24.2, 6.3]$ mm, $\mathbf{q}_{\mathrm{ref}}$, ${}^{g}_{I}\mathbf{q}_{\mathrm{ref}}$: $(\mathbf{e}, 0^\circ) \pm (\mathbf{e}, 9.5^\circ)$ for $\forall\, \mathbf{e} \in \mathbb{R}^3 \setminus \{\mathbf{0}\}$ (angle-axis)

- Kalibr frequently fails, our method always succeeds showing consistent performance

Averaged Results over 21 Trajectories in *Ill-lit* Condition

	Kalibr	Our Method
RMSE in $\mathbf{p}$ [mm]	107.42	1.37
RMSE in $\mathbf{q}$ [deg]	1.81	4.19
RMSE in ${}^{g}_{I}\mathbf{q}$ [deg]	1.03	3.51
computation time [ms]	7.83 ± 0.28	5.16 ± 0.55
success rate	2 / 21	21 / 21

$\mathbf{p}$: relative position, $\mathbf{q}$: relative orientation, ${}^{g}_{I}\mathbf{q}$: gyroscope misalignment

$\mathbf{p}_{\text{ref}}: [100, 100, 0] \pm [24.2, 24.2, 6.3]$ mm, $\mathbf{q}_{\text{ref}}$, ${}^{g}_{I}\mathbf{q}_{\text{ref}}: (\mathbf{e}, 0°) \pm (\mathbf{e}, 9.5°)$ for $\forall\, \mathbf{e} \in \mathbb{R}^3 \setminus \{\mathbf{0}\}$ (angle-axis)

- Kalibr mostly fails, our method always succeeds showing consistent performance

Conclusion

- We proposed a multi-IMU extrinsic calibration only using measurements collected along arbitrary trajectories
- We suggested constructing and solving a nonlinear least-square problem that addresses not only the extrinsic parameters but also gyroscope misalignment
- We showed our method is applicable to even in the conditions that a benchmark using an aiding sensor may fail

Please come and visit our Git repo!
https://github.com/jongwonjlee/mix-cal

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