Challenges and Opportunities for Visual Inertial Navigation of Aerial Robots

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Workshop Visual Inertial Navigation Systems

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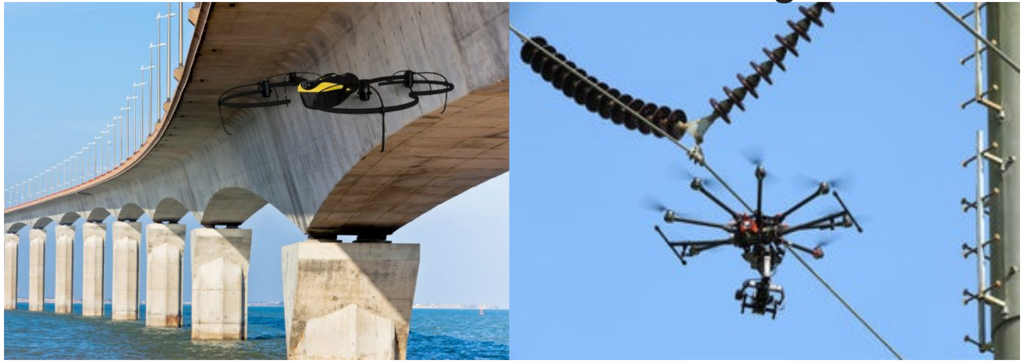
Opportunities

Photography

Infrastructure Monitoring



Search and rescue

Air Delivery

Precision Agriculture

Entertainment

Past

D. Mellinger, N. Michael, V. Kumar, “Precise and Aggressive Maneuvers for Autonomous Quadrotors”, IJRR 2012

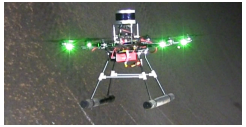
M Müller, S Lupashin, R D'Andrea, “Quadrotor ball juggling”, IROS 2011

- Limitations
  - Motion capture systems, pilots, and GPS
  - Known environment
  - Flight time
  - Limited Power: Size and Payload constraints
  - No environment interaction

Small Size and Autonomy?

Autonomy

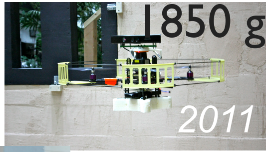
2016



4500 g

3000 g

Lightweight and low power Perception!

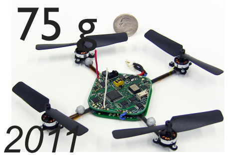


Mass ~ Kinetic Energy

Small Mass → Safety

$$\text{max ang. acceleration} \sim \frac{1}{L}$$

Small = Agile



Size

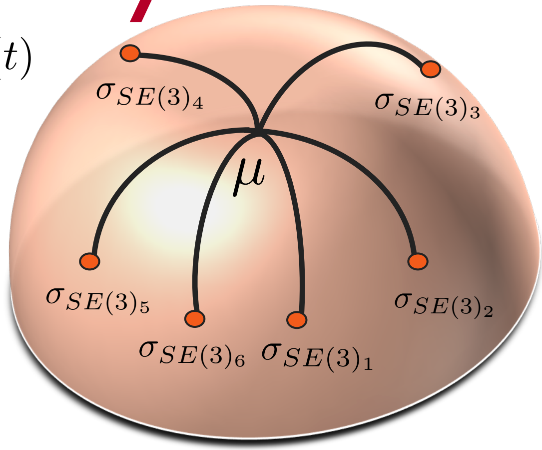
Visual Inertial Odometry

- UKF with Sigma points on SE(3)

Orientation	Euler angles	Quaternion	Axis-angle	Rotation Matrix
Global	No	Yes	Yes	Yes
Unique	No	No	No	Yes

$$\sigma_{SE(3)_0} = \mathbf{x}_{SE(3)},$$
$$\sigma_{SE(3)_i} = \mathbf{x}_{SE(3)} \exp_{SE(3)} \left(\pm \sqrt{(\lambda + N)\, \mathbf{P}_a(k)} \right),$$
$$i = 1, \cdots 2N.$$

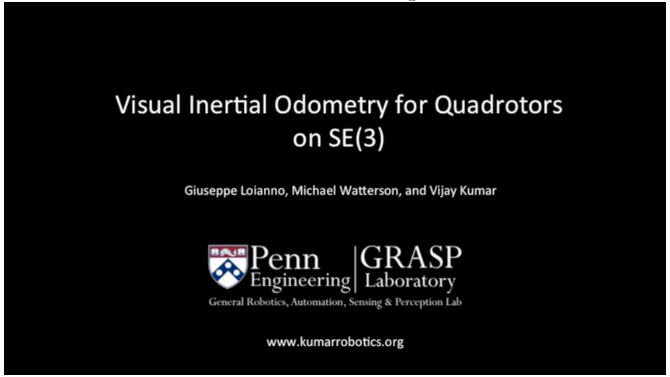
$$\dot{\mathbf{T}}_C^W(t) = \mathbf{T}_C^W(t) \cdot \widehat{\xi}(t)$$
$$\dot{\mathbf{v}}(t) = \mathbf{a}(t)$$
$$\dot{\mathbf{b}}_a(t) = \eta_{b_a}(t)$$
$$\dot{\mathbf{b}}_\omega(t) = \eta_{b_\omega}(t)$$
$$\dot{\gamma} = 0$$



Manifold representation

- Measurement by detected landmarks in the current frame

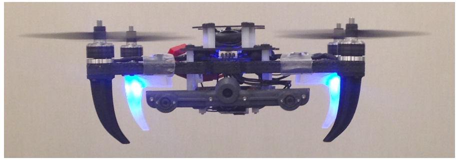
$$\mathbf{y}_i = \begin{bmatrix} u_i \\ v_i \end{bmatrix} + \mathbf{n}_i, \quad \lambda \begin{bmatrix} u_i \\ v_i \\ 1 \end{bmatrix} = \Pi \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} g(k) \begin{bmatrix} X_i \\ Y_i \\ Z_i \\ 1 \end{bmatrix}$$



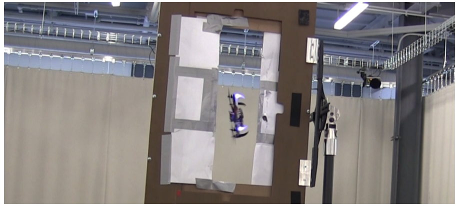
G. Loianno et al. "**Visual Inertial Odometry for Quadrotors on SE(3)**", ICRA 2016

Navigation in Constrained Environment

- Fast and agile autonomous navigation
  - On-board navigation at 500 Hz
  - Dynamic feasible trajectories with physical constraints
  - Non-linear control with no switches
  - **5 m/s speeds, accelerations 1.5 g, 90 degrees and 800 deg/s**



250g 4 cameras and IMU



The vehicle flying through a narrow gap

Disaster area

G. Loianno, C. Brunner, G. McGrath, and V. Kumar, "**Estimation, Planning and Control for Aggressive Flight with a Small Quadrotor with Single Camera and IMU**", RA-L 2016 and ICRA 2017, Featured **IEEE Spectrum, Popular Science, Popular Mechanics, Quartz**

Estimation, Control and Planning for Aggressive Flight with a Small Quadrotor with a Single Camera and IMU

Giuseppe Loianno
Vijay Kumar

Chris Brunner
Gary McGrath

Penn Engineering | GRASP Laboratory
General Robotics, Automation, Sensing & Perception Lab

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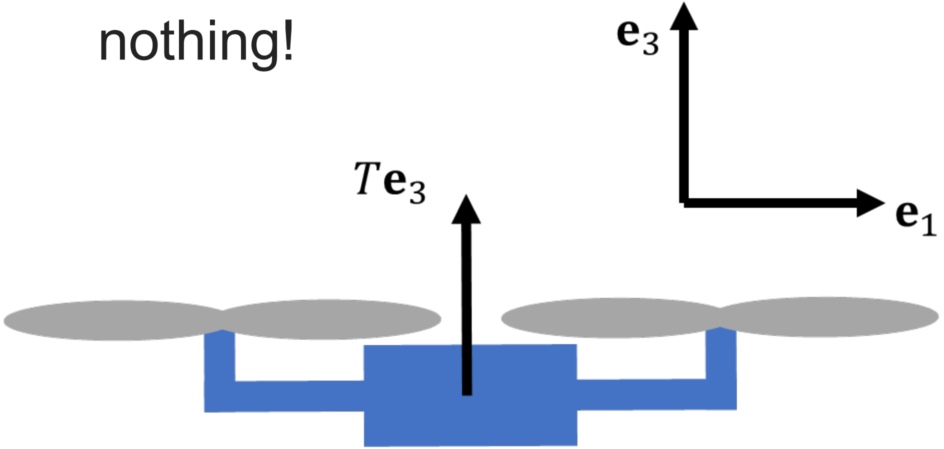
www.kumarrobotics.org

Why a Better Model is Needed

- Current IMU models are general purposes, but do not incorporate the system physical aspects

- IMU “erroneously” used in the prediction

- Under the standard model, the accelerometer measurement tells us nothing!



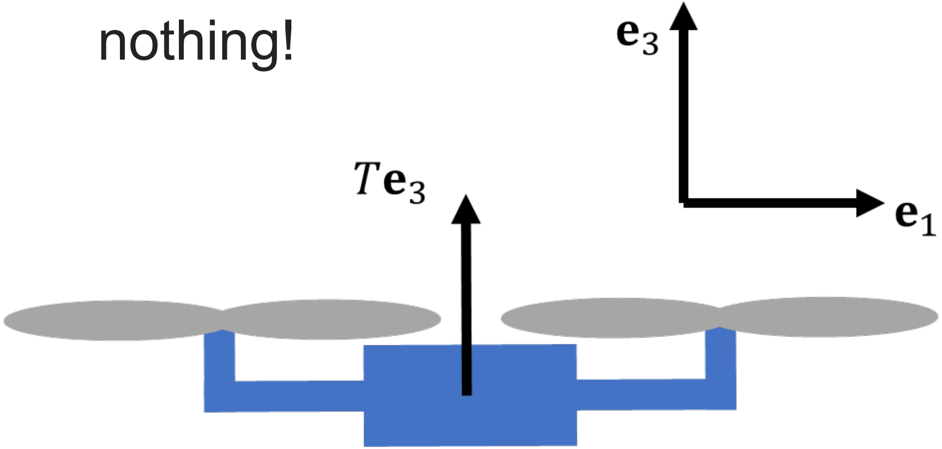
$$
\begin{aligned}
m\mathbf{a}_{\text{meas}} &= R^\top\left(\sum \mathbf{F}_i + mg\mathbf{e}_3\right) \\
&= R^\top\left(T\mathbf{b}_3 - mg\mathbf{e}_3 + mg\mathbf{e}_3\right) \\
&= T\mathbf{e}_3
\end{aligned}
$$

Why a Better Model is Needed

- Current IMU models are general purposes and based on kinematics, but do not incorporate the system physical properties

- IMU erroneously used in the prediction as control input

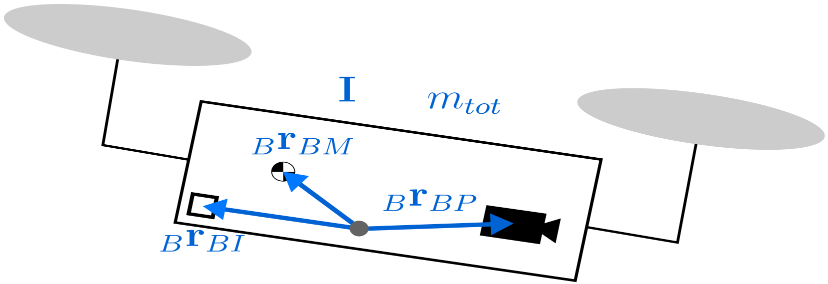
- Under the standard model, the accelerometer measurement tells us nothing!



$$
\begin{aligned}
m\mathbf{a}_{\text{meas}} &= R^\top\left(\sum \mathbf{F}_i + mg\mathbf{e}_3\right)\\
&= R^\top\left(T\mathbf{b}_3 - mg\mathbf{e}_3 + mg\mathbf{e}_3\right)\\
&= T\mathbf{e}_3
\end{aligned}
$$

Physical Parameters

- How do we guarantee correct vehicle performances?
- How do we quickly adapt to changes in vehicle configuration?
- How do we certify that the vehicle is ready to perform autonomous flight?



m_{tot}	Mass
$\mathbf{I}$	Moment of Inertia
${}_{B}\mathbf{r}_{BM}$	Center of Mass
${}_{B}\mathbf{r}_{BP}$	Pose Sensor
${}_{B}\mathbf{r}_{BI}$	IMU

V. Wuest, V. Kumar, and G. Loianno, "**Online Estimation of Geometric and Inertia Parameters for Multirotor Aerial Vehicles**", IEEE International Conference on Robotics and Automation ICRA 2019
https://github.com/arplaboratory/GeomInertiaEstimator

Model

- The state is represented by

$$\mathbf{x}(t) = \begin{bmatrix} \mathbf{x}_t(t) \\ \mathbf{x}_c \end{bmatrix} \qquad \mathbf{x}_t(t) = \begin{bmatrix} {}_W\mathbf{r}_{WM}(t) \\ {}_W\mathbf{v}_{WM}(t) \\ \mathbf{q}_{WM}(t) \\ \mathbf{\Omega}(t) \end{bmatrix} \qquad \mathbf{x}_c = \begin{bmatrix} m \\ \mathrm{diag}({}_M\mathbf{I}) \\ {}_B\mathbf{r}_{BM} \\ {}_B\mathbf{r}_{BP} \\ {}_B\mathbf{r}_{BI} \\ \mathbf{b}_a \\ \mathbf{b}_\Omega \end{bmatrix}$$

- The system model can be written as

$${}_W\dot{\mathbf{r}}_{WM} = {}_W\mathbf{v}_M \qquad {}_W\dot{\mathbf{v}}_M = \frac{1}{m}\,\mathbf{R}(\mathbf{q}_{WM})\;{}_M\mathbf{F}_{tot} - g\;\mathbf{e}_z$$

$$\dot{\mathbf{q}}_{WM} = \tfrac{1}{2}\mathbf{q}_{WM} \otimes \mathbf{\Omega} \qquad \dot{\mathbf{\Omega}} = {}_M\mathbf{I}^{-1}\left({}_M\mathbf{M}_{tot} - \mathbf{\Omega} \times ({}_M\mathbf{I}\;\mathbf{\Omega})\right)$$

- The measurement updates are provided by the IMU and pose sensor

V. Wuest, V. Kumar, and G. Loianno, “**Online Estimation of Geometric and Inertia Parameters for Multirotor Aerial Vehicles**”, IEEE International Conference on Robotics and Automation ICRA 2019
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Online Estimation of Geometric and Inertia Parameters for Multirotor Aerial Vehicles

Valentin Wüest, Vijay Kumar, and Giuseppe Loianno

Penn Engineering | GRASP Laboratory
General Robotics, Automation, Sensing & Perception Lab

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Small Scale Drones

Problem: Can we use the IMU to estimate the attitude and 3D velocity in a drift-free manner?

Impact: All quadrotors equipped with IMU

- Limited payload, e.g. nano-scale quadrotors
- Vision systems may fail

Challenges

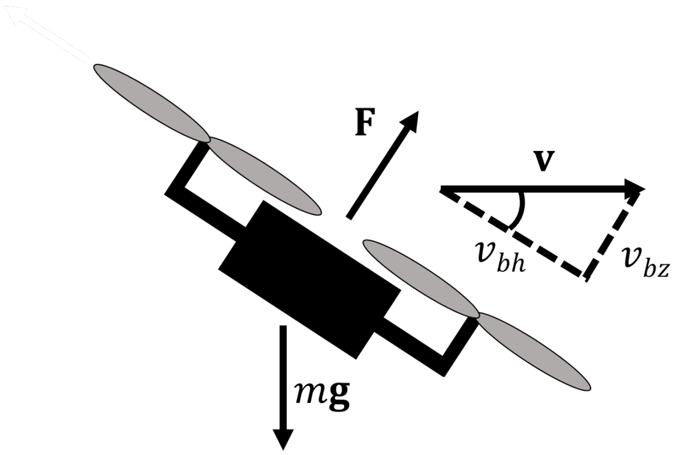
- Low cost IMUs are noisy, with drifting bias
- Velocity and attitude not directly measured

Example of a nano-scale UAV, the Crazyflie 2.0

Camera Failure

J. Svacha, K. Mohta, M. Watterson, G. Loianno and V. Kumar, "**Inertial Attitude Estimation for Quadrotors**", IROS 2018
J. Svacha, G. Loianno, and V. Kumar, "**Inertial Yaw-Independent Velocity and Attitude Estimation for High Speed Quadrotor Flight**", RA-L 2019 and ICRA 2019

Contributions



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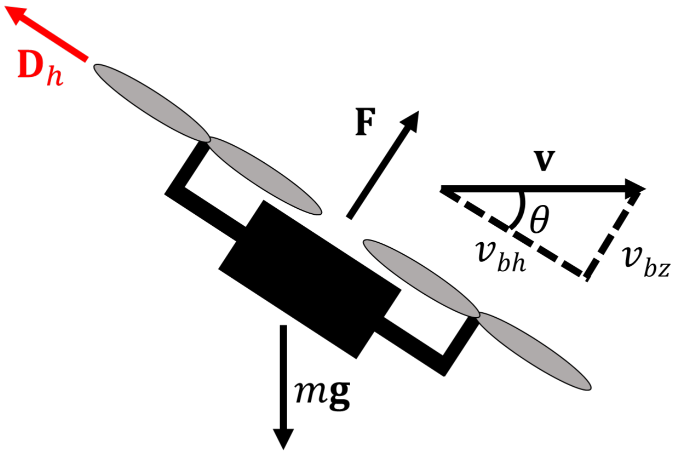
Contributions

Previous:

- Estimation of 2D velocity, roll, and pitch and drag coefficient with IMU



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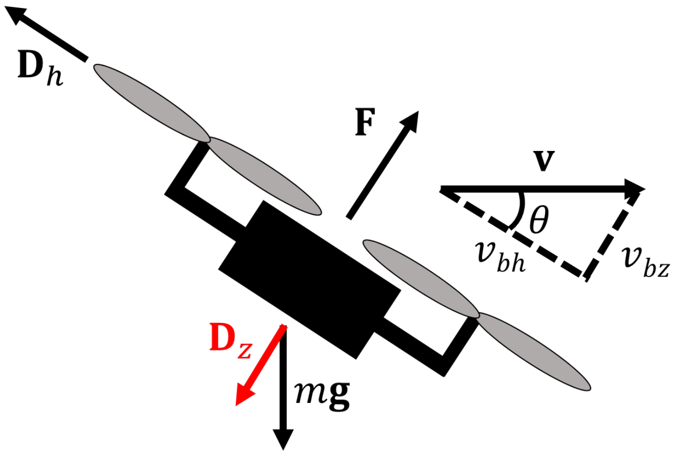
Contributions

<u>Previous:</u>

- Estimation of 2D velocity, roll, and pitch and drag coefficient with IMU
- Extended linear drag model to z direction
  $$m\dot{\mathbf{v}} = \mathbf{F} - RDR^{\top}\mathbf{v} + m\mathbf{g}$$
  $$D = \mathrm{diag}(k_d \quad k_d \quad k_{dz})$$
- 3D velocity and tilt



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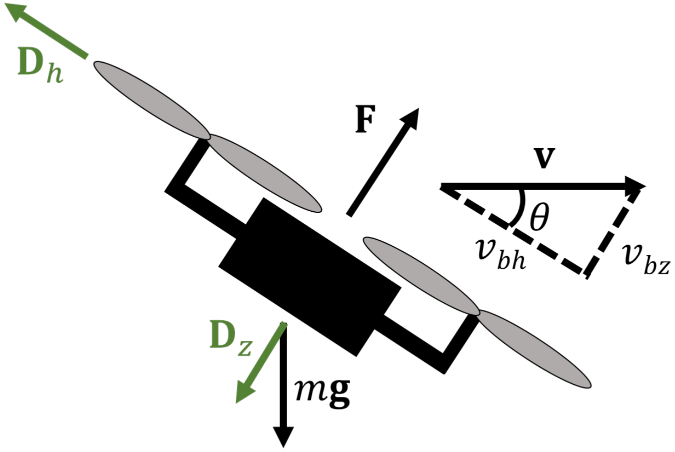
J. Svacha, G. Loianno, and V. Kumar, "**Inertial Yaw-Independent Velocity and Attitude Estimation for High Speed Quadrotor Flight**", RA-L 2019 and ICRA 2019

Contributions

Previous:

- Estimation of 2D velocity, roll, and pitch and drag coefficient with IMU[1]
- Extended linear drag model to z direction[2]

$$m\dot{\mathbf{v}} = \mathbf{F} - RDR^{\top}\mathbf{v} + m\mathbf{g}$$
$$D = \mathrm{diag}(k_d \quad k_d \quad k_{dz})$$



Current: Using **only IMU** to estimate:

- 3D velocity and tilt
- Thrust and drag coefficients
- **Accelerometer biases**

J. Svacha, K. Mohta, M. Watterson, G. Loianno and V. Kumar, "**Inertial Attitude Estimation for Quadrotors**", IROS 2018
J. Svacha, G. Loianno, and V. Kumar, "**Inertial Yaw-Independent Velocity and Attitude Estimation for High Speed Quadrotor Flight**", RA-L 2019 and ICRA 2019

Dynamic Model

What can the IMU be used to estimate? We employ an UKF to estimate

- Body-frame velocity $\mathbf{v}_b$
- Tilt (two degrees of freedom of R)
- k_f, k_d, and k_z
- Accelerometer bias

$$\mathbf{x} = \begin{pmatrix} \psi & \mathbf{z}^\top & \mathbf{v}^\top & \mathbf{b}^\top & \mathbf{k}^\top \end{pmatrix}^\top$$

$$\dot{\mathbf{v}} = \frac{k_f}{m} u_{ss} \mathbf{e}_3 - \frac{u_s}{m} D\mathbf{v} - g R_z(\pi)\mathbf{z} - \boldsymbol{\omega} \times \mathbf{v} + \boldsymbol{\eta}_v$$

$$\dot{\psi} = \omega_3 - \frac{\omega_1 z_1 + \omega_2 z_2}{1 + z_3} + \eta_\psi$$

$$\dot{\mathbf{z}} = -R_z(\pi)[\boldsymbol{\omega}]_\times R_z(\pi)\mathbf{z}$$

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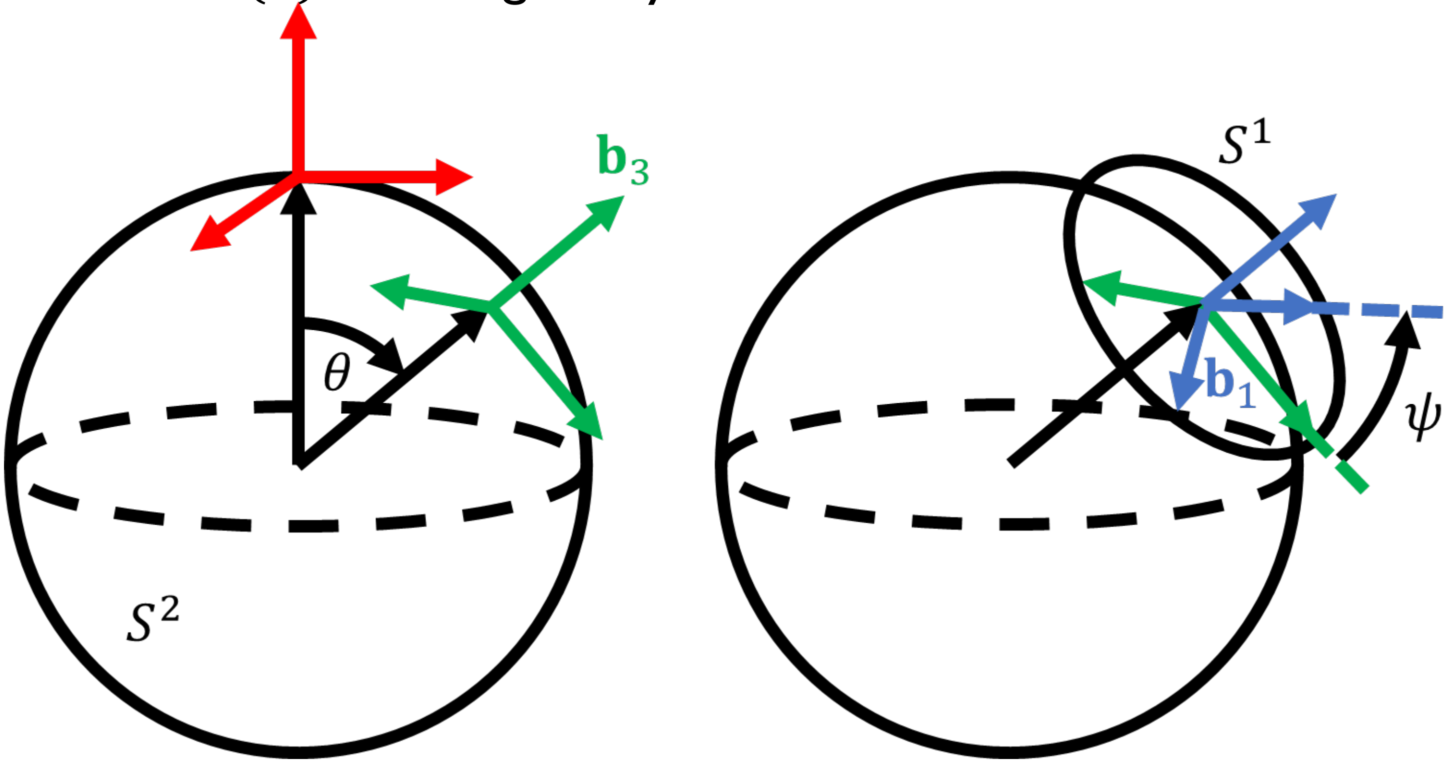
Parameterizing Rotation

Hopf fibration: $SO(3)$ almost globally looks like $S^2 \times S^1$



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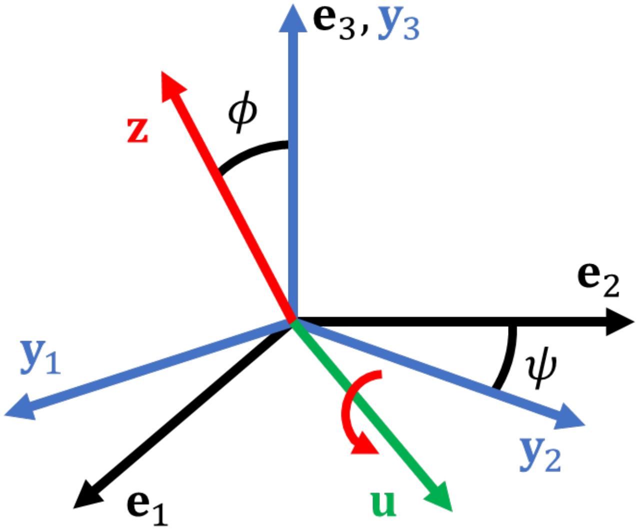
Yaw-Tilt Convention

$$R = R_\psi R_{tilt}\left(\mathbf{z}\right)$$

$$R = \begin{pmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix} \exp\left(\phi[\mathbf{u}_\times]\right)$$

$$\mathbf{u} = \frac{\mathbf{e}_3 \times \mathbf{z}}{\|\mathbf{e}_3 \times \mathbf{z}\|}$$



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Yaw-Tilt Convention

We write the orientation as

$$R = R_\psi R_{tilt}\left(\mathbf{z}\right)$$

$$\begin{aligned}
\dot{R}_{tilt}\left(\mathbf{z}\right) &= \dot{R}_\psi^\top R + R_\psi^\top \dot{R} \\
&= -[\dot{\psi}\mathbf{e}_3]_\times R_\psi^\top R + R_\psi^\top R[\boldsymbol{\omega}]_\times \\
&= -[\dot{\psi}\mathbf{e}_3]_\times R_\phi + R_\phi[\boldsymbol{\omega}]_\times .
\end{aligned}$$

$$\dot{\mathbf{z}} = -R_z(\pi)[\boldsymbol{\omega}]_\times R_z(\pi)\mathbf{z}$$

$\dot{\mathbf{z}}$ is independent of ψ**!**

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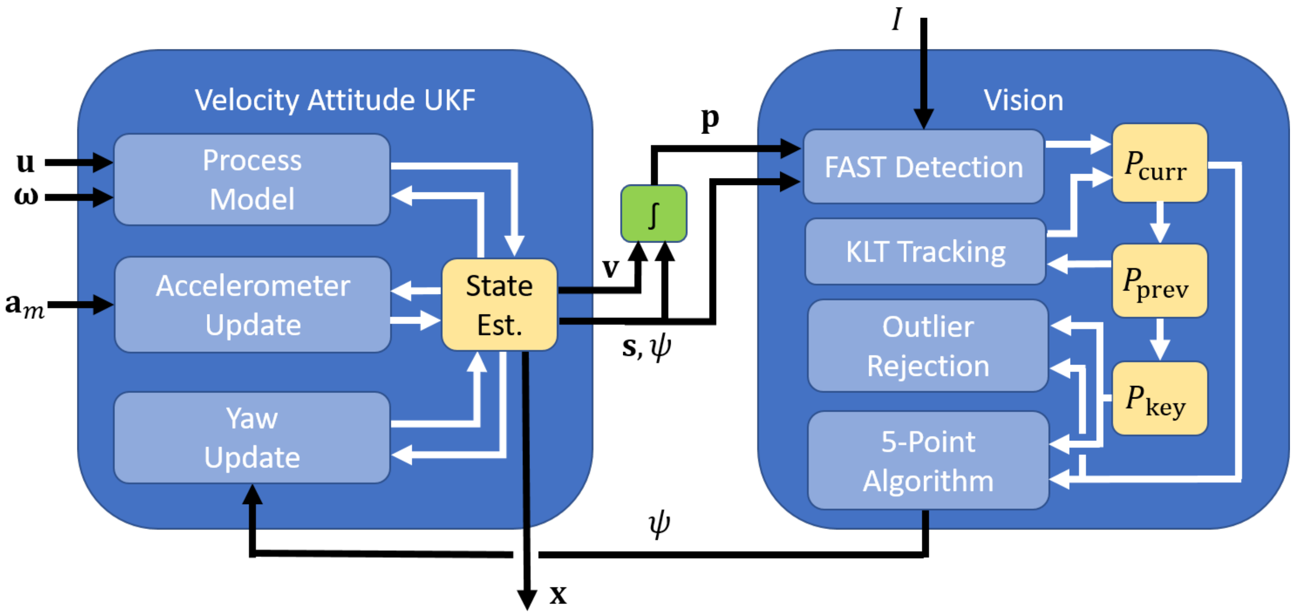
Yaw Estimation

- IMU alone cannot be used to estimate yaw
- How can a camera be used to do it in a faster way with the underlying inertial filter?



Measurement Update

The measurement update is provided by the yaw

$$y_1 = \psi + \nu_\psi$$

and the acceleration provided by the IMU

$$\mathbf{y}_2 = \frac{k_f}{m} u_{ss} \mathbf{e}_3 - \frac{u_s}{m} D\mathbf{v} + \mathbf{b} + \boldsymbol{\nu}_a$$

Inertial Yaw-Independent Velocity and Attitude Estimation for High Speed Quadrotor Flight

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Newton-Euler Dynamics

We design a 32 state UKF

$$\boldsymbol{x} = \begin{pmatrix} \boldsymbol{s}^\top & \boldsymbol{v}^{\mathcal{B}\top} & \boldsymbol{\omega}^{\mathcal{B}\top} & \boldsymbol{b}^{\mathcal{B}\top} & \boldsymbol{u}^\top & \boldsymbol{I}^\top & \boldsymbol{k}^\top \end{pmatrix}^\top$$

Translational part dynamics with drag on each motor hub speed

$$m\frac{d}{dt}(\boldsymbol{v}^{\mathcal{B}}) = \sum_{i=1}^{4}(k_f u_i^2 \boldsymbol{e}_3 - \boxed{u_i D \boldsymbol{v}_i^{\mathcal{B}})} - m(gR^\top \boldsymbol{e}_3 + \boldsymbol{\omega}^{\mathcal{B}} \times \boldsymbol{v}^{\mathcal{B}})$$

Rotational part dynamics

$$J\frac{d}{dt}(\boldsymbol{\omega}^{\mathcal{B}}) = \sum_{i=1}^{4} \boxed{\boldsymbol{M}_i^{\mathcal{B}}} - \boldsymbol{\omega}^{\mathcal{B}} \times J\boldsymbol{\omega}^{\mathcal{B}} \qquad \boldsymbol{M}_i = \boldsymbol{M}_{i,\text{force}} + \boldsymbol{M}_{i,\text{flap}} + \boldsymbol{M}_{i,\text{yaw}}$$

$$\boldsymbol{M}_{i,\text{force}} = \boldsymbol{r}_i \times \boldsymbol{F}_i \qquad \boldsymbol{M}_{i,\text{flap}} = k_{\text{flap}} u_i \boldsymbol{v}_i \times \boldsymbol{b}_3$$

$$\boldsymbol{M}_{i,\text{yaw}} = -\epsilon_i (k_\tau (u_{ci} - u_i) + k_m u_i^2) \boldsymbol{b}_3$$

J. Svacha, J. Paulos, G. Loianno, and V. Kumar, “**IMU-Based Inertia Estimation for a Quadrotor Using Newton-Euler Dynamics**”, RA-L 2020 and ICRA 2020

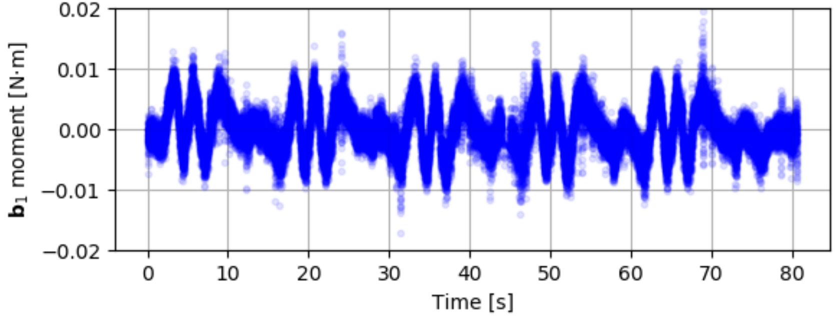
Flapping Moment

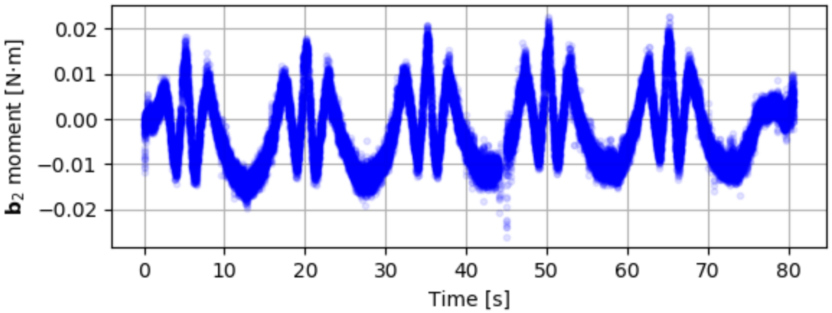
Compare terms predicted by model with those measured by sensors

$$J\dot{\boldsymbol{\omega}} \approx \boldsymbol{M}$$

IMU moment "measurement" $\boldsymbol{M}_{\mathrm{IMU},k} = J\dfrac{\hat{\boldsymbol{\omega}}_k - \hat{\boldsymbol{\omega}}_{k-1}}{\Delta t}$

Model moment prediction $\boldsymbol{M}_{\mathrm{model},k} = \sum_{i=1}^{4} \hat{\boldsymbol{r}}_{i,k} \times \hat{\boldsymbol{F}}_i - \hat{\boldsymbol{\omega}} \times J\hat{\boldsymbol{\omega}}$





$$\Delta\boldsymbol{M}_k = \boldsymbol{M}_{\mathrm{IMU},k} - \boldsymbol{M}_{\mathrm{model},k}$$

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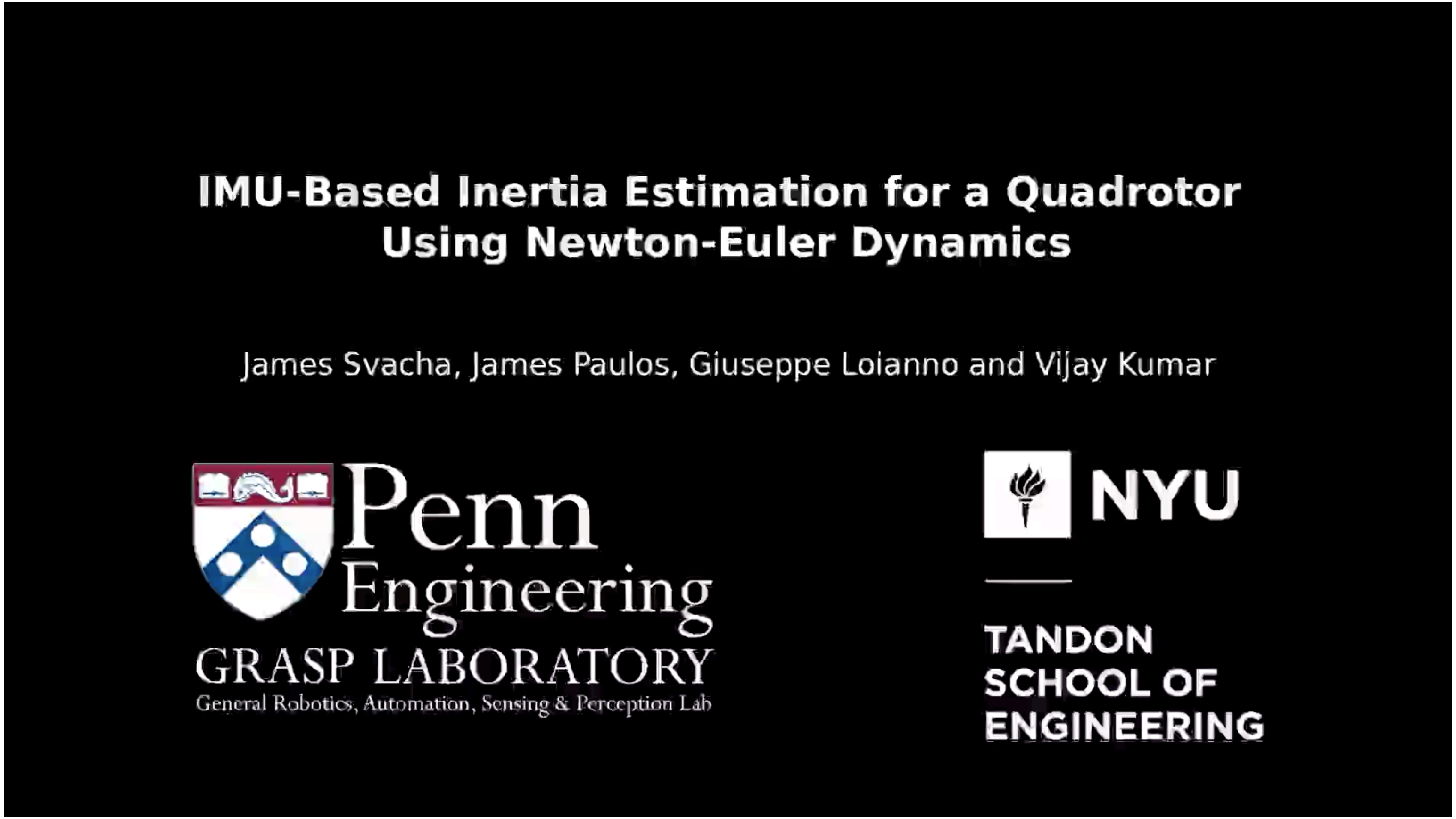
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Conclusion

- New refined and more accurate models reveals the possibility to estimate additional and more accurate system properties
- Useful for navigation re-initialiazation or alternative to existing VINS
- Help tracking control performances
- **Combine current visual-inertial navigation techniques with dynamic models**
- **Coupling and co-design of perception and action**

Acknowledgments

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ARMY RESEARCH LABORATORY

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TEPCO

MBZIRC
تحدي محمد بن زايد العالمي للروبوت
Mohamed Bin Zayed International Robotics Challenge

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Thank You

Questions?

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