An Aerodynamic Model-aided State Estimator for Multirotor UAVs

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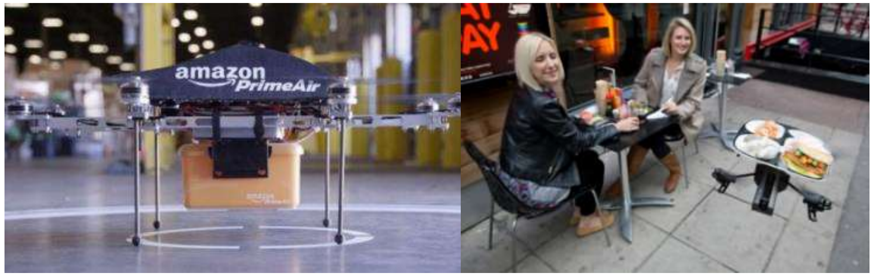
Multi-rotor UAVs

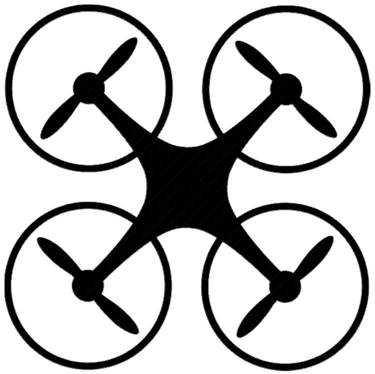
Agriculture

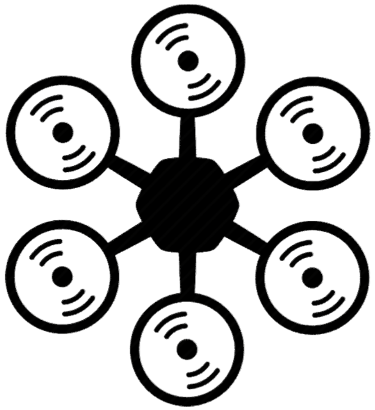
Entertainment



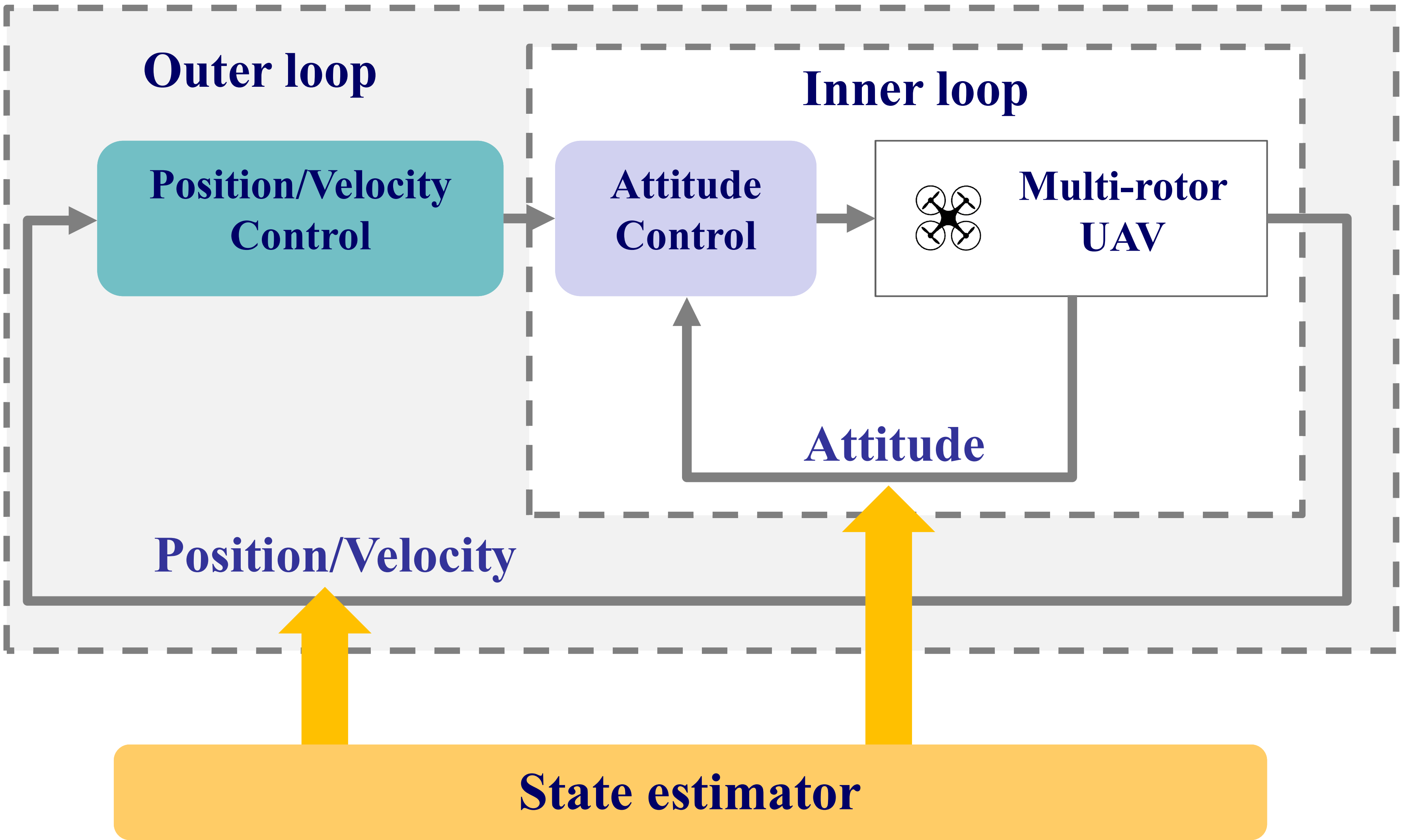
Service robots

Photography

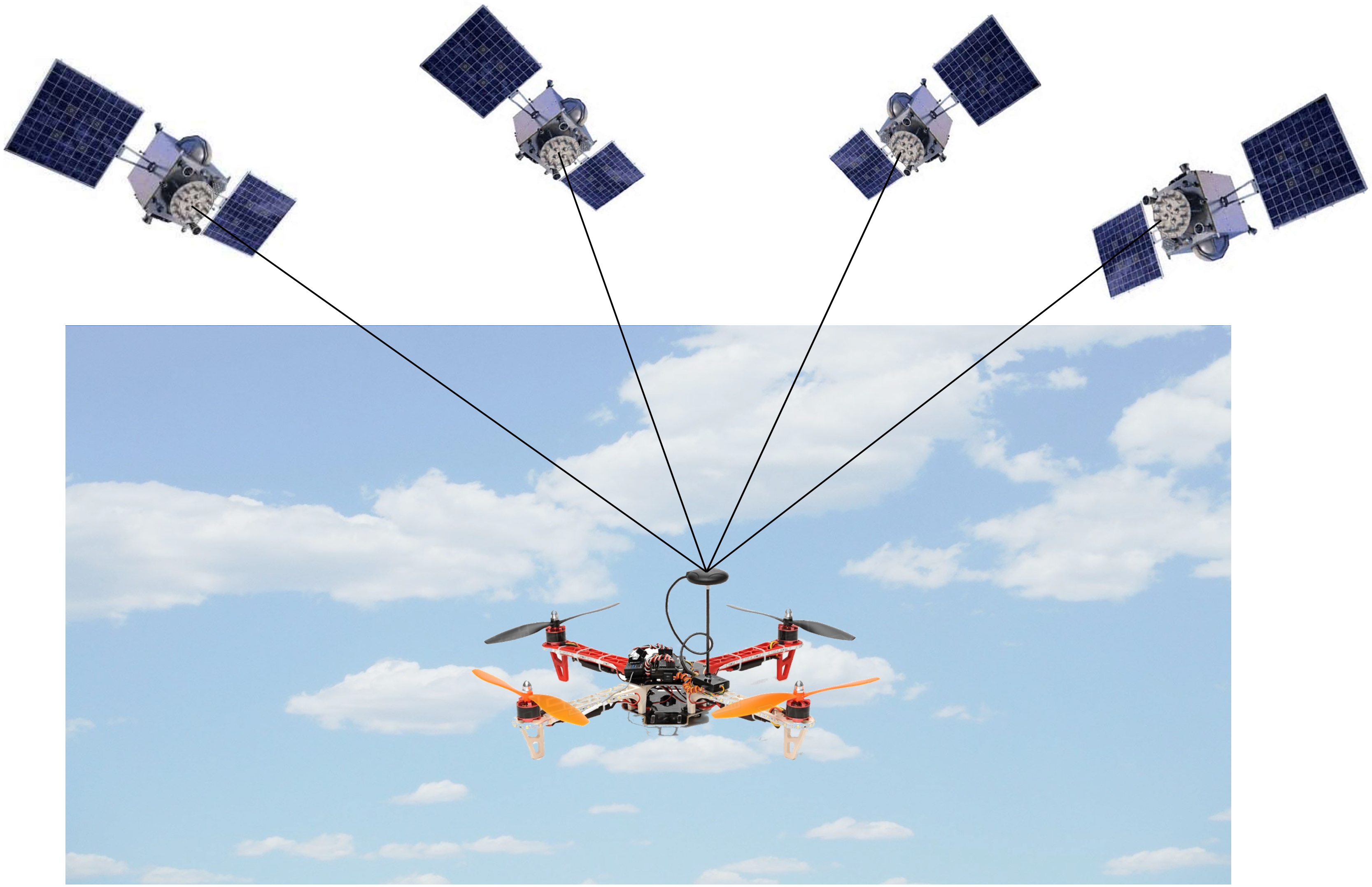




A typical control loop of a multi-rotor UAV



Open area



GPS-denied environments

Vision-based State Estimator:

Optical flow + Ultrasonic sensor

Visual odometry/SLAM

Visual-inertial odometry/SLAM

PX4flow

VI sensor

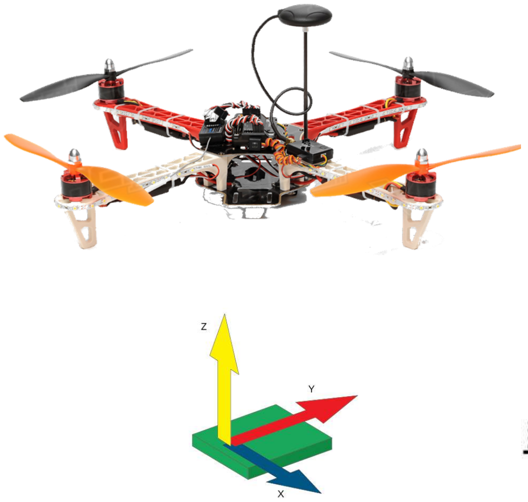
DJI Guidance

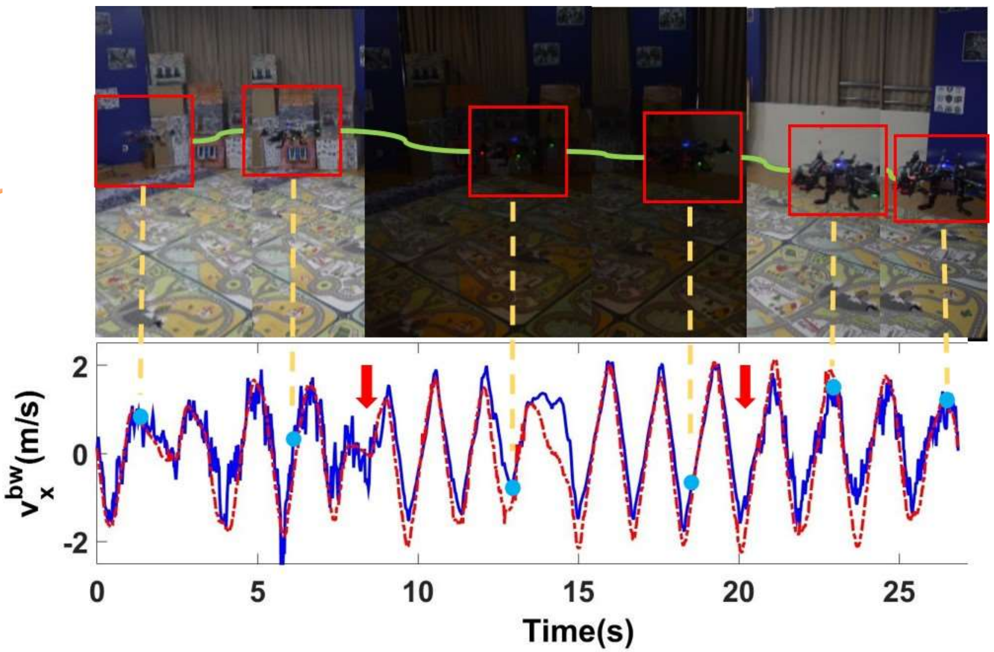
Texture-less
Dark scenes
Over-exposure

Aerodynamic model-aided state estimator

Special aerodynamic characteristic of multi-rotor UAVs:

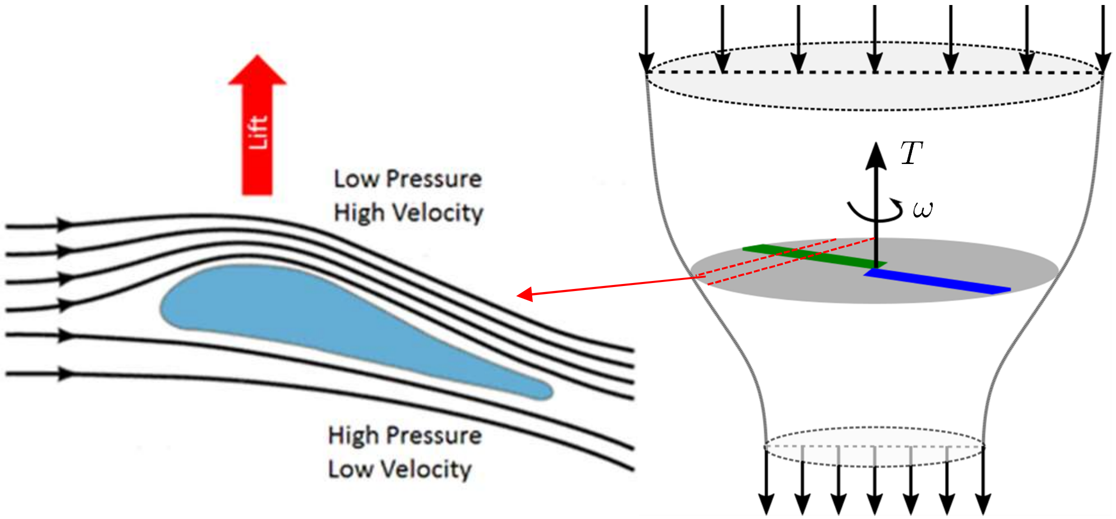
The horizontal velocity of the vehicle is observable from the accelerometer measurements.





Rotor Aerodynamics

- Force in hovering state



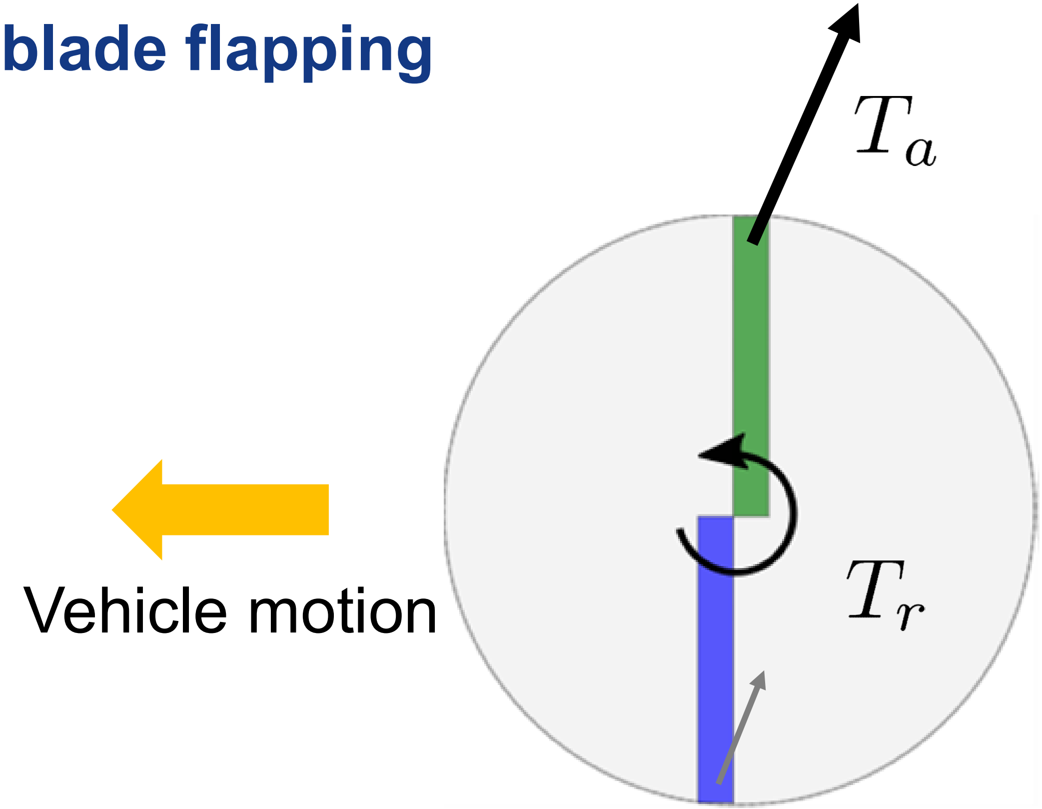
$$T = c_T \omega^2$$

The thrust force T

1) is perpendicular to the rotor plane
2) is proportional to the square of the spinning speed of the rotor

Rotor Aerodynamics

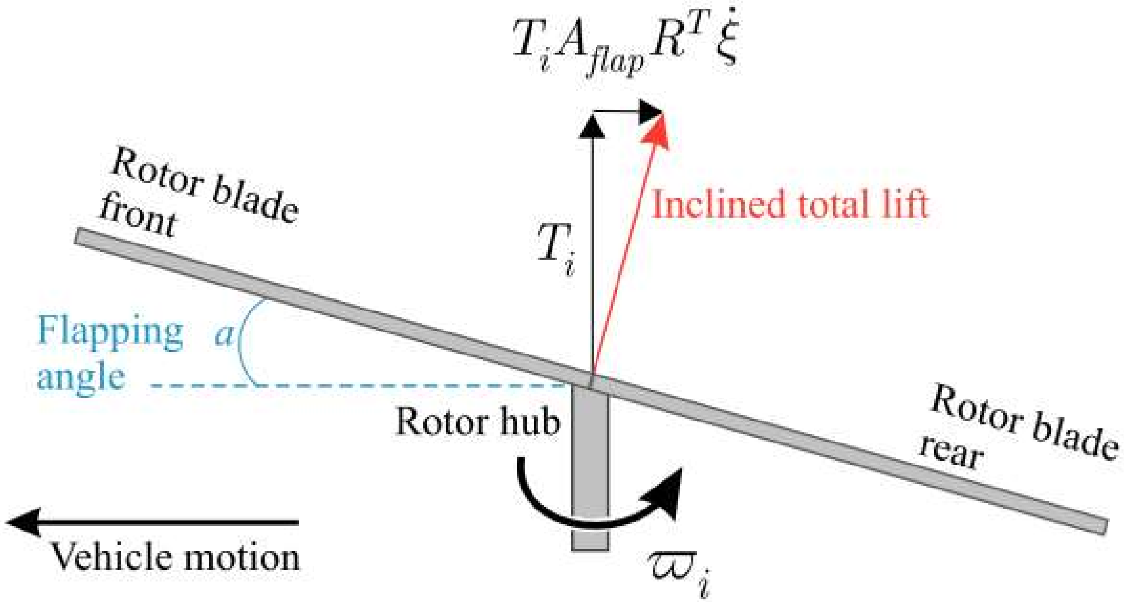
- Forces in translation movement :
  - **blade flapping**



$T_a > T_r$

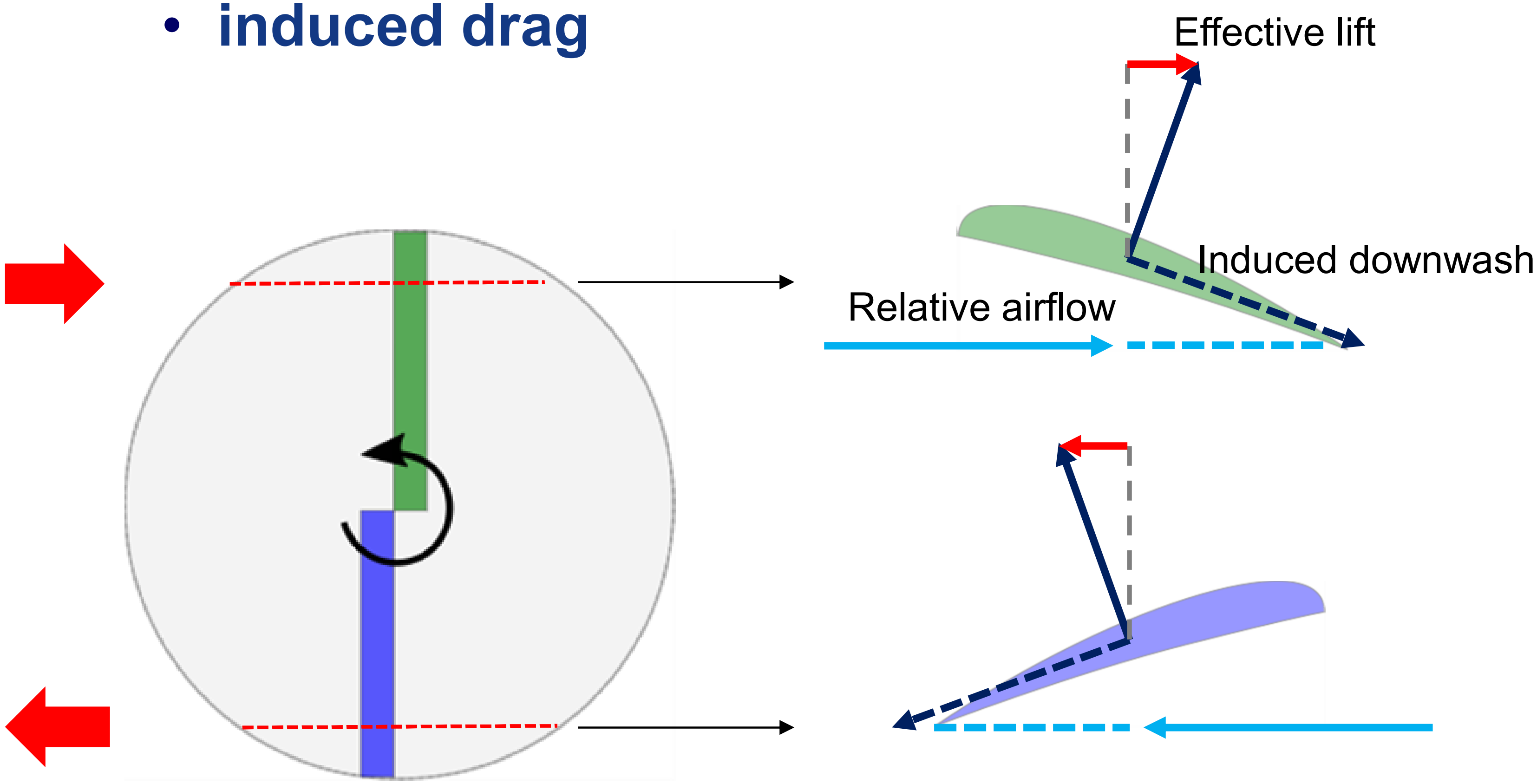
Rotor Aerodynamics

- Forces in translation movement：
  - **blade flapping**



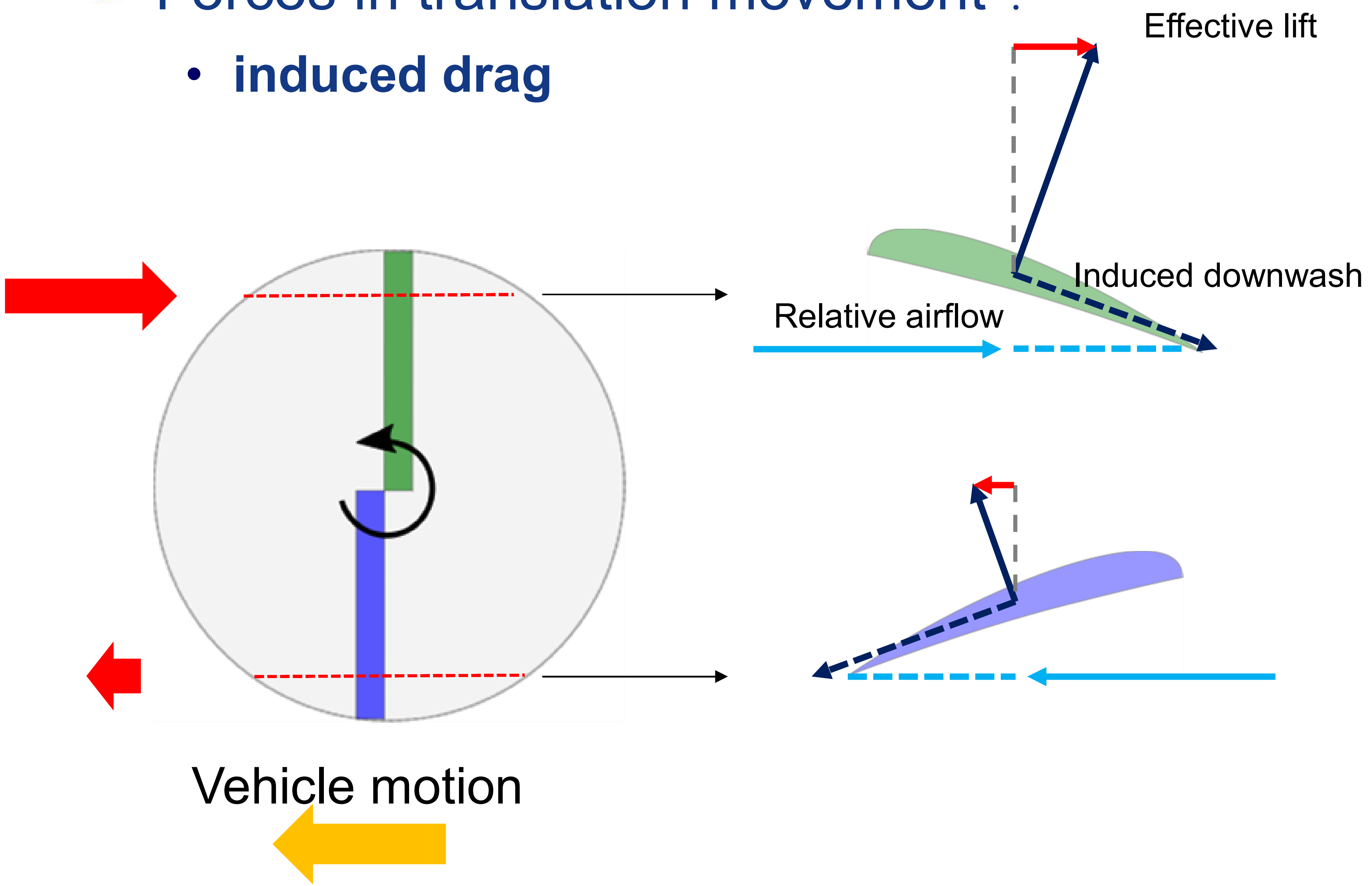
Rotor Aerodynamics

- Induced drag in hovering：
  - **induced drag**



Rotor Aerodynamics

- Forces in translation movement：
  - **induced drag**



Rotor Aerodynamics

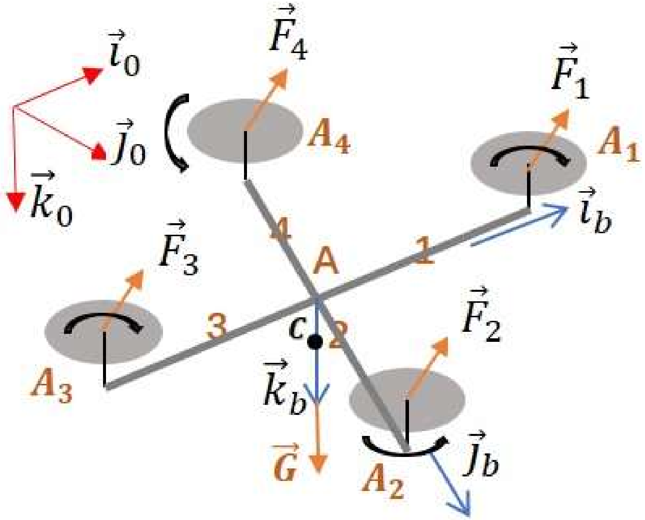
- When the UAV is in translation flight, it receives an horizontal force that is a combination of blade-flapping force and the induced drag,

$$H_i \approx \underbrace{\lambda}_{\text{constant}} \underbrace{\omega_i}_{\text{Spinning speed of the rotor}} \underbrace{V_C^{\perp}}_{\text{Horizontal velocity in body frame}}$$

Principles of Helicopter Aerodynamics, Section 3.5

Multi-rotor Aerodynamics

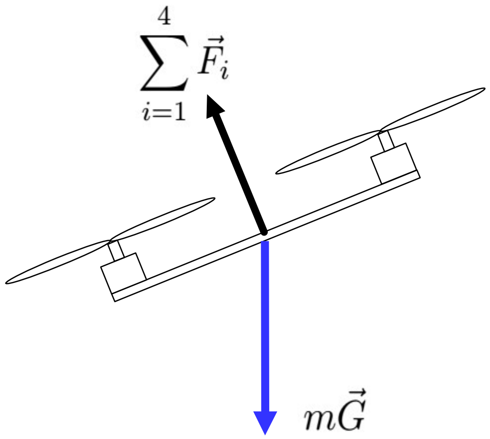
- The total force generated by the rotors:



$$\sum_{i=1}^{4} \vec{F}_i \approx -a\left(\sum_{i=1}^{4} \omega_i^2\right)\vec{k}_b - \lambda_1\left(\sum_{i=1}^{4} \omega_i\right)\vec{V}_C^{\perp}$$

Martin, Philippe, and Erwan Salaün. "The true role of accelerometer feedback in quadrotor control." Robotics and Automation (ICRA), 2010 IEEE International Conference on. IEEE, 2010.

Multi-rotor Aerodynamics



1) Accelerometer measures the special force (exclude the gravity) :

$$\sum_{i=1}^{4} \vec{F}_i \approx -\alpha\left(\sum_{i=1}^{4} \omega_i^2\right)\vec{k}_b - \lambda\left(\sum_{i=1}^{4} \omega_i\right)\vec{V}_C^{\perp}$$

2) Dynamic model from Newton's Second law:

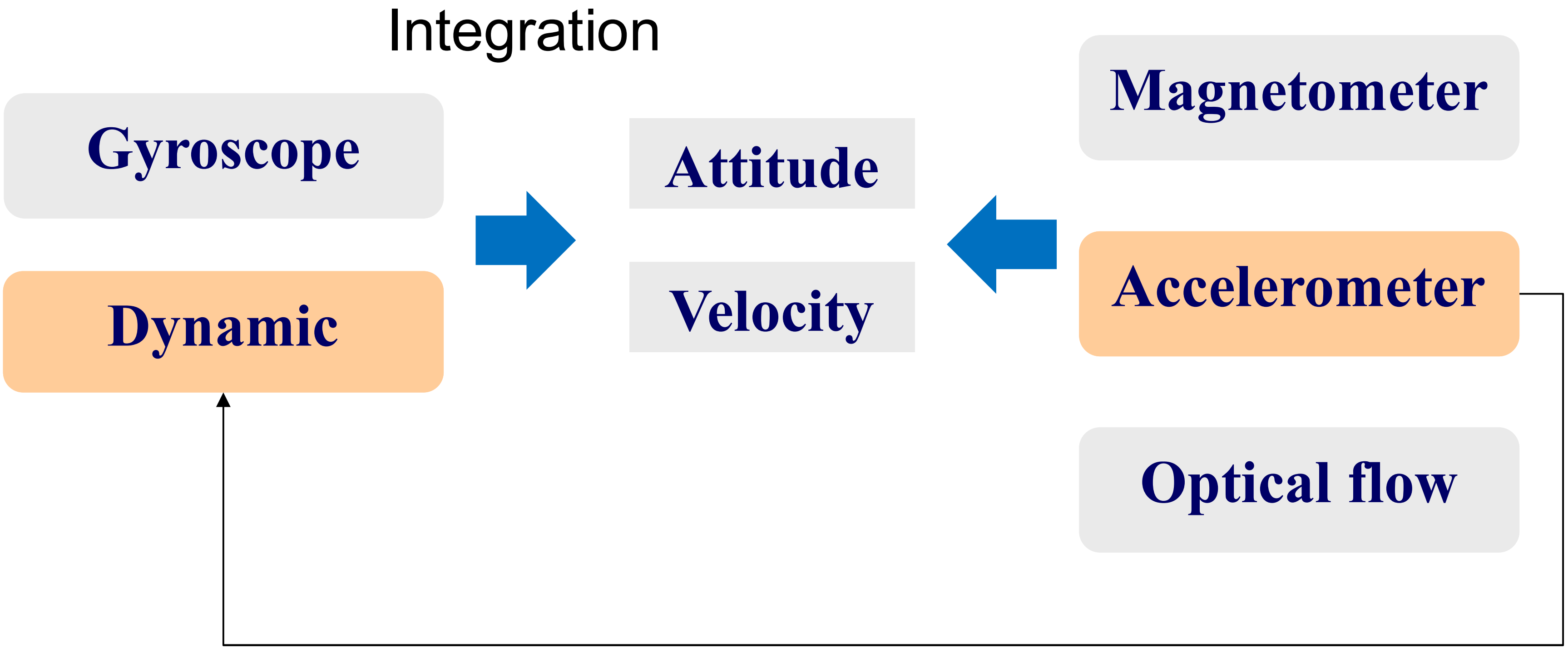
$$\vec{F}_C = m\dot{\vec{V}}_C = m\vec{G} - \alpha\left(\sum_{i=1}^{4} \omega_i^2\right)\vec{k}_b - \lambda\left(\sum_{i=1}^{4} \omega_i\right)\vec{V}_C^{\perp}$$

$$\begin{aligned}\dot{\vec{V}}_C^b &= (-G\sin\theta - \mu\cdot v_x^b - (\omega_y^b v_z^b - \omega_z^b v_y^b))\vec{i}_b \\ &+ (G\cos\theta sin\phi - \mu\cdot v_y^b - (\omega_z^b v_x^b - \omega_x^b v_z^b))\vec{j}_b \\ &+ (G\cos\theta\cos\phi - a_z - (\omega_x^b v_y^b - \omega_y^b v_x^b))\vec{k}_b\end{aligned}$$

Multi-rotor Aerodynamics

- **Two cues of multi-rotor aerodynamics:**
  - Body velocities in the rotor plane is observable
  - Roll/pitch angle is observable*

Aerodynamic model-aided state estimator



Estimator Design

State definition & propagation:

$$\mathbf{x} = [\ \phi\ \theta\ \psi\ \beta_{g_x}\ \beta_{g_y}\ \beta_{g_z}\ v_x^b\ v_y^b\ v_z^b\ h\ \mu_x\ \mu_y\ ]^T \quad \} \text{ state vector}$$

$$\begin{cases}
\dot{\phi} = \hat{\omega}_x^b + \hat{\omega}_y^b tan\theta sin\phi + \hat{\omega}_z^b tan\theta cos\phi & \\
\dot{\theta} = \hat{\omega}_y^b cos\phi - \hat{\omega}_z^b sin\phi & \text{attitude} \\
\dot{\psi} = \hat{\omega}_y^b sin\phi / cos\theta + \hat{\omega}_z^b cos\phi / cos\theta & \\
\dot{\beta}_{g_x^b} = -\frac{1}{\tau_{g_x^b}} \beta_{g_x^b} + \delta_{\beta_{g_x}} & \\
\dot{\beta}_{g_y^b} = -\frac{1}{\tau_{g_y^b}} \beta_{g_y^b} + \delta_{\beta_{g_y}} & \text{imu bias} \\
\dot{\beta}_{g_z^b} = -\frac{1}{\tau_{g_z^b}} \beta_{g_z^b} + \delta_{\beta_{g_z}} & \\
\dot{v}_x^b = -g sin\theta + \mu_x v_x^b - (\hat{\omega}_y^b v_z^b - \hat{\omega}_z^b v_y^b) & \\
\dot{v}_y^b = g cos\theta sin\phi + \mu_y v_y^b - (\hat{\omega}_z^b v_x^b - \hat{\omega}_x^b v_z^b) & \text{velocity} \\
\dot{v}_z^b = g cos\theta cos\phi + a_z - (\hat{\omega}_x^b v_y^b - \hat{\omega}_y^b v_x^b) & \\
\dot{h} = -sin\theta v_x^b + cos\theta sin\phi v_y^b + cos\theta cos\phi v_z^b & \text{height} \\
\dot{\mu}_x = \delta\mu_x & \text{aerodynamic coefficients} \\
\dot{\mu}_y = \delta\mu_y, &
\end{cases}$$

Estimator Design

Measurement Model

$$\mathbf{x} = [\ \phi\ \theta\ \psi\ \beta_{g_x}\ \beta_{g_y}\ \beta_{g_z}\ v_x^b\ v_y^b\ v_z^b\ h\ \mu_x\ \mu_y\ ]^T$$

state vector

$$\begin{cases} Acc_x = \mu_x \cdot v_x^b + \delta_{a_x^b} \\ Acc_y = \mu_y \cdot v_y^b + \delta_{a_y^b} \\ \hat{v}_x^b = v_x^b + \delta_{v_x^b} \\ \hat{v}_y^b = v_y^b + \delta_{v_y^b} \\ \hat{\psi} = \psi + \delta_\psi \\ \hat{h} = h + \delta_h \end{cases}$$

accelerometer

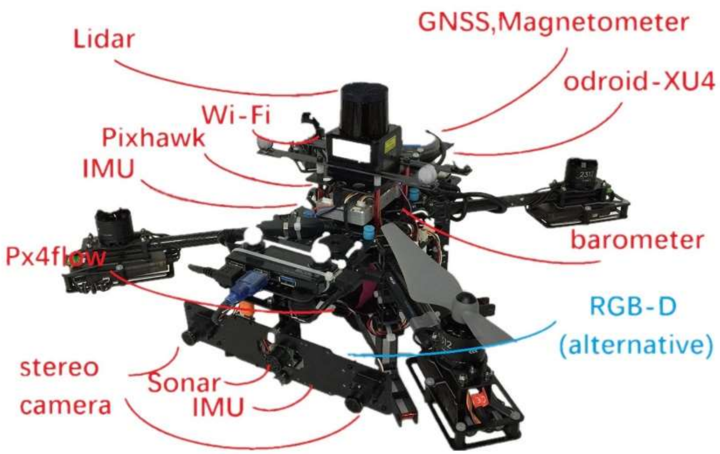
optical flow

magnetometer

sonar

Experiment

- We test our estimator in real scenes with real platforms:

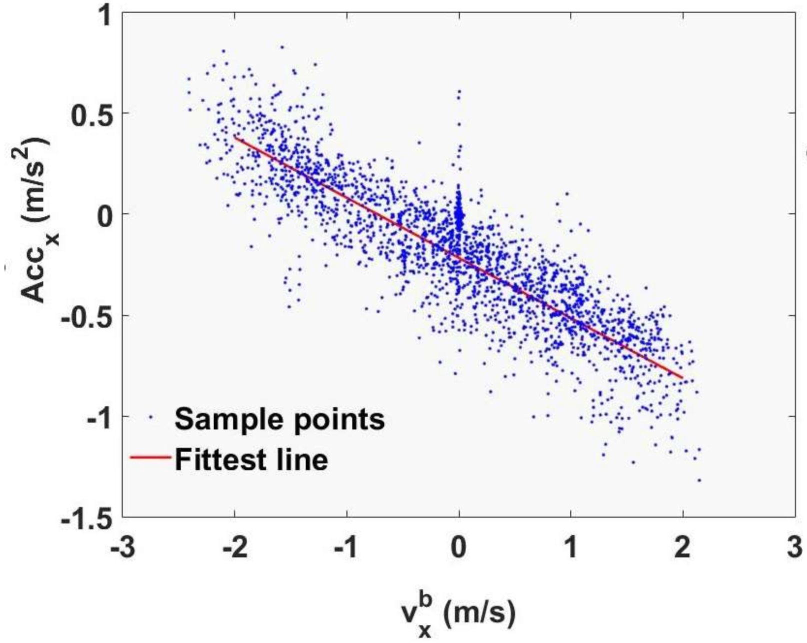


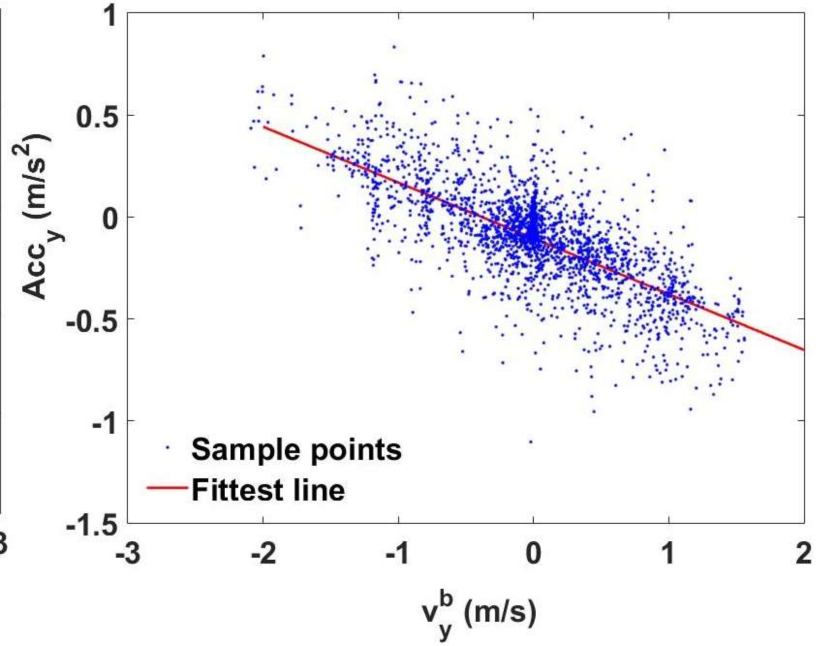
Our home-made quadcopter	Parrot's ARDrone 2.0
Onboard computation	Off board computation

Experiment

- Drag Coefficients Initialization by line fitting

$$\tilde{\mu}_x = \min_{\mu_x}(Acc_x - \mu_x v_x^b)^2 \qquad \tilde{\mu}_y = \min_{\mu_y}(Acc_y - \mu_y v_y^b)^2$$

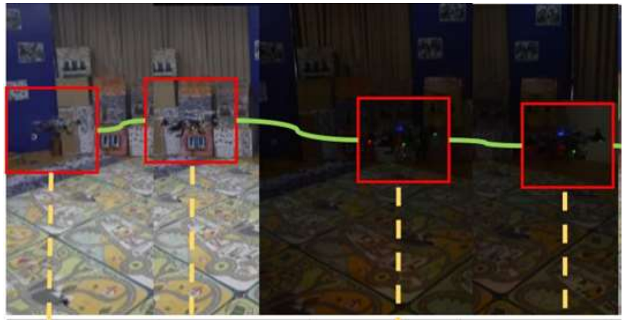




Left: line fitting of μ_x, **Right**: line fitting of μ_y

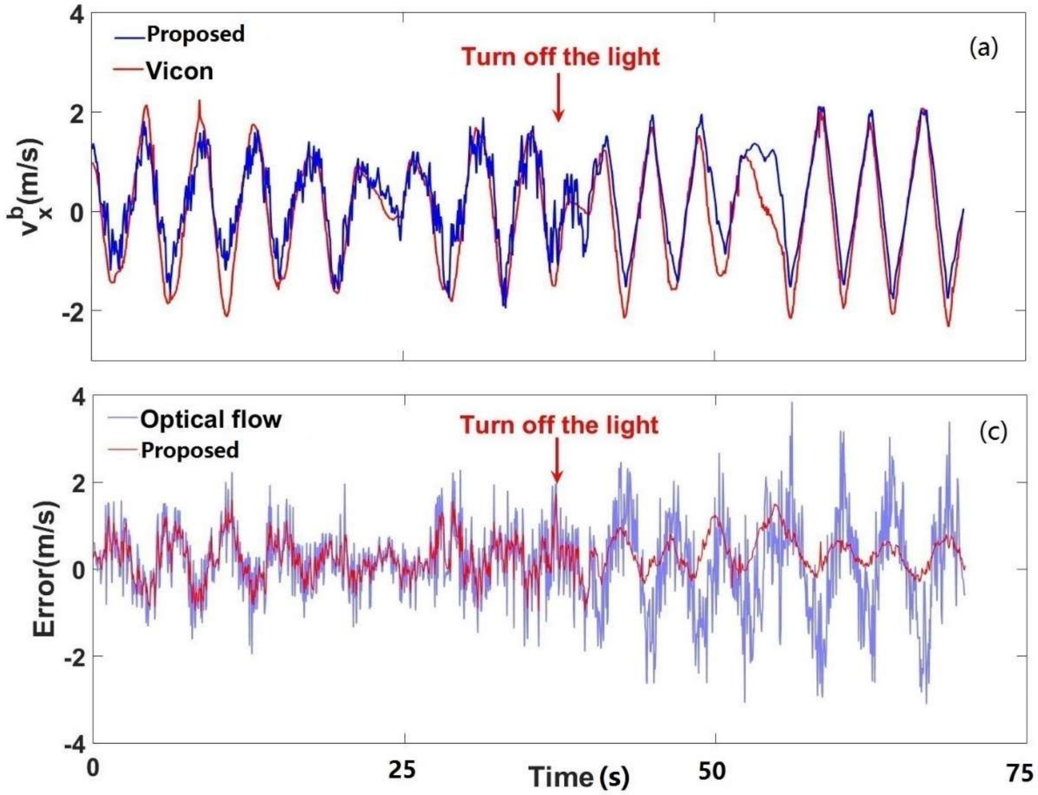
Experiment

- Manual flight under controlled lighting condition



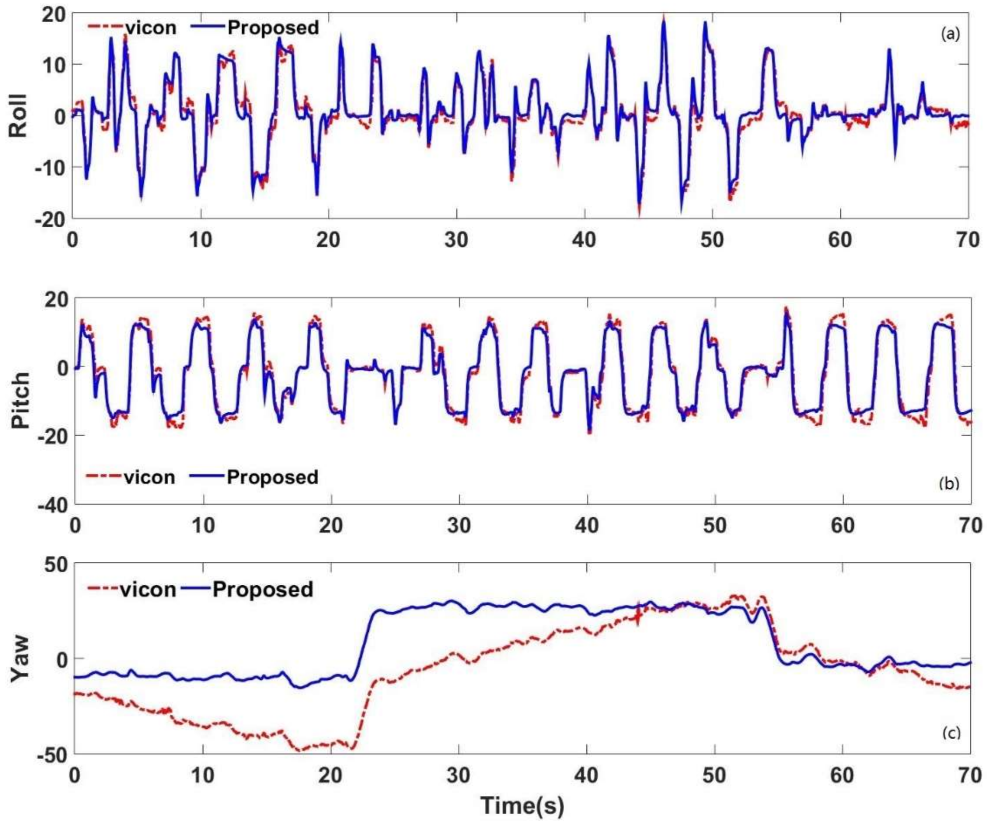
	Light on	Light off
O.F	0.355m/s	0.893/ms
D.E.	0.322m/s	0.349m/s

Average estimation error (m/s)



Experiment

- Autonomous flight in complete darkness (Attitude estimation)



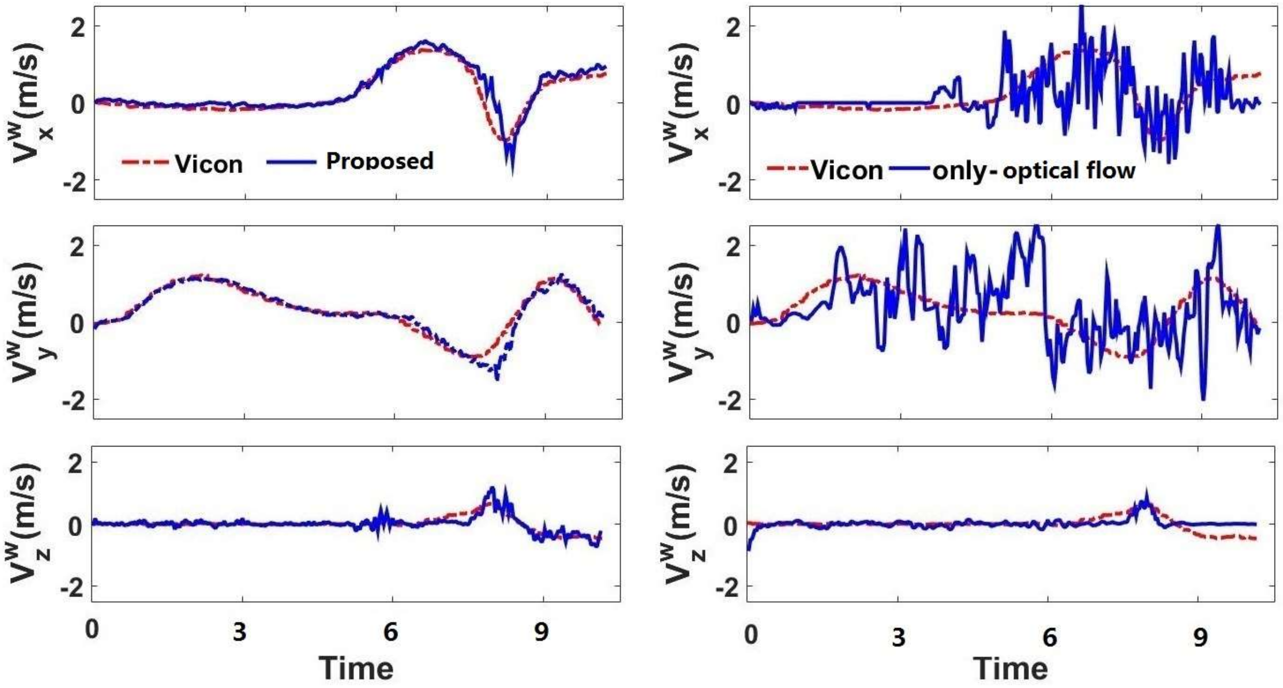
	mean	STD
Roll	0.235°	1.359°
Pitch	0.172°	2.024°
Yaw	14.79°	13.70°

Estimation error (°)

Yaw is not observable

Experiment

- Autonomous flight in complete darkness (Velocity estimation)

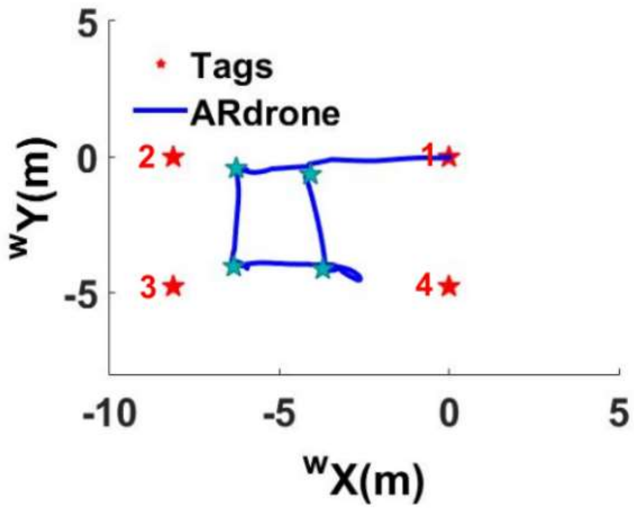


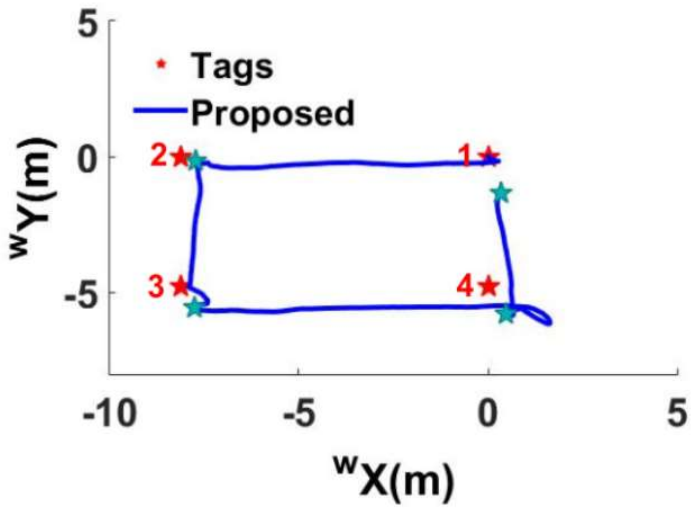
**Optical flow is not usable, but the proposed estimator works well*

Experiment

- Manual flight in a large hall at night

	Estimated Distance (m)	Loop Error
ARDrone	16.00	4.13
Proposed	25.81	1.37





Conclusion

- Special aerodynamics of multi-rotor UAVs renders the body velocity and attitude observable.
- By incorporating this observation, we can design a fast and easily implemented state estimator to remedy the shortcoming of vision-based approach.
- The results of real-world experiments show the effectiveness and robustness of the proposed approach.

Q&A


Experiment #1
Velocity estimation under large illumination change