Wind tolerant controller and robust INS/GPS sensor fusion architecture for multirotor UAV

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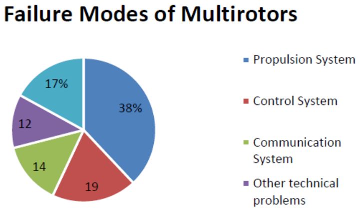
12 Octobre 2018

Motivations

UAVs Reliability

UAV crash

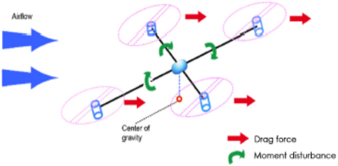


Failure rate on a conventional aircraft

[1] S. Reimann, J. Amos, E. Bergquist, J. Cole, J. Phillips, S. Shuster, UAV for Reliability, AEM 4331 - Aerospace Vehicle Design, December 2013.

Problem formulation

Wind pertubations on system



- Additional uncertainties
- Induced disturbance forces and moments
- Loss of stability

Problem formulation

Onboard sensors vulnerable to hardware faults

IMU

Barometer

GPS unit

Compass

Aim of Our Work

- Maintaining system performance and stability in the presence of model uncertainties and external perturbations.
- Developing a strategy to cope with sensor faults.

Main Contributions

- Proposition of a nonlinear observer based on super-twisting theory to estimate the wind forces.
- Proposition of new EKF based GPS/INS fusion architecture to detect and isolate faulty sensors and software issues.

Platform

Quadrotor S500 frame

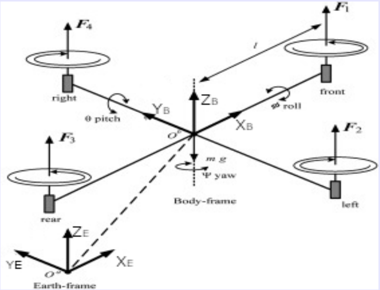
System's Parameters

Mass m	1.1 kg
Inertia I_{xx}, I_{yy}	$2.2 * 10^{-2} Kg.m^2$
Inertia I_{zz}	$5.5 * 10^{-2} Kg.m^2$
Thrust factor K_f	$2.75 * 10^{-5} Ns^2/rad^2$
Drag factor K_t	$3.6 * 10^{-7} Nm/rad^2$
Length of the arm l	0.22 m
Rotor's Inertia J_r	negligible

The thrust and torque coefficients are provided by the manufacturer (www.dji.com).

State variables and Control inputs

Schematic representation



O_b:$\{O_B, X_B, Y_B, Z_B\}$ Body-fixed frame

O_E:$\{O_E, X_E, Y_E, Z_E\}$ Earth-fixed frame

State Variables

position	x,y
altitude	z
roll	ϕ
pitch	θ
yaw	ψ
roll velocity	p
pitch velocity	q
yaw velocity	r

Virtual control inputs

Total thrust	u_t
roll torque	τ_ϕ
pitch torque	τ_θ
yaw torque	τ_ψ

Real inputs

motors speeds ω_i $i = 1, ..4$

NonLinear Model

The Quadrotor's dynamics are written as [5]:

$$\begin{cases} \ddot{x} = (\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi) * \frac{u_t}{m} \\ \ddot{y} = (\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi) * \frac{u_t}{m} \\ \ddot{z} = (\cos\phi\cos\theta)\frac{u_t}{m} - g \\ \ddot{\phi} = \frac{I_{yy}-I_{zz}}{I_{xx}}\dot{\theta}\dot{\psi} - \frac{J_r}{I_{xx}}\dot{\theta}\Omega + \frac{1}{I_{xx}}\tau_\phi \\ \ddot{\theta} = \frac{I_{zz}-I_{xx}}{I_{yy}}\dot{\phi}\dot{\psi} - \frac{J_r}{I_{yy}}\dot{\phi}\Omega + \frac{1}{I_{yy}}\tau_\theta \\ \ddot{\psi} = \frac{I_{xx}-I_{yy}}{I_{zz}}\dot{\phi}\dot{\theta} + \frac{1}{I_{zz}}\tau_\psi \end{cases} \quad (1)$$

The relation between the virtual inputs and the motors speeds:

$$\begin{cases} u_t = F_1 + F_2 + F_3 + F_4 \\ \tau_\phi = (F_4 - F_2) * l \\ \tau_\theta = (F_3 - F_1) * l \\ \tau_\psi = (\tau_1 + \tau_3) - (\tau_2 + \tau_4) \end{cases} \quad (2)$$

[5] S. Bouabdallah, "Design and Control of Quadrotors With Application to Autonomous Flying," Ph.D thesis, Ecole Polytechnique Federale de Lausanne, 2007.

Generalities

nonlinear system general form

$$x^{(n)} = f(x, \dot{x}, \ddot{x}, ..., x^{(n-1)}, t) + g(x, \dot{x}, \ddot{x}, ..., x^{(n-1)}, t)u + w(t) \quad (3)$$

- $x^{(n)}$: state vector
- u : virtual input vector
- f : modeled dynamics function
- g : control function
- $w(t)$: unmodeled dynamics

Uncertain functions Boundaries

$$\begin{aligned} |f(\underline{x}, t) - \hat{f}(\underline{x}, t)| &\leq F(\underline{x}, t) \\ |g(\underline{x}, t) - \hat{g}(\underline{x}, t)| &\leq G(\underline{x}, t) \\ |w(\underline{x}, t) - \hat{w}(\underline{x}, t)| &\leq W(\underline{x}, t) \\ |\dot{w}(\underline{x}, t) - \dot{\hat{w}}(\underline{x}, t)| &\leq \delta(\underline{x}, t) \end{aligned} \quad (4)$$

Sliding variable

- Defining the tracking error as :

$$\tilde{x} = x - x_d \tag{5}$$

- Introducing sliding variable :

$$s = \dot{\tilde{x}} + \lambda \tilde{x} \tag{6}$$

Sliding variable properties

$$s \begin{cases} \dot{s} \quad contains \quad u \\ s \longmapsto 0 \quad when \quad t \longmapsto +\infty \Rightarrow \tilde{x} \longmapsto 0 \end{cases} \tag{7}$$

Lyapunov function

- Positive definite Lyapunov function :

$$V(t) = \frac{1}{2}s^2 \tag{8}$$

- Control law :

$$u = \frac{1}{\hat{g}}(\hat{u} - k * sign(s))$$
$$\hat{u} = -\hat{f} + \ddot{x}_d + \lambda\dot{\tilde{x}} \tag{9}$$

Lyapunov condition

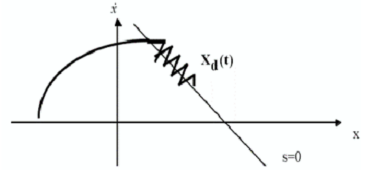
$$\dot{V}(t) = s\dot{s} = s(f - \hat{f}) + w(t)s - k|s| \leq -\eta|s| < 0 \tag{10}$$

- To ensure this condition:

Gain

$$k = F + W + \eta \tag{11}$$

Problems

1) Chattering → 

2) Over-estimation of F & W → Motor saturation & chattering

3) Under-estimation of F & W → Possibility of Lyapunov instability

Solutions

- Chattering

Super-twisting algorithm

$$u(t) = u_1 + u_2 \begin{cases} u_1 = -\alpha_1 |s|^{\tau} \text{sign}(s), & \tau \in]0,\ 0.5] \\ \dot{u}_2 = -\alpha_2 \text{sign}(s) \end{cases} \quad (12)$$

- Over/under-estimation of F :

Observer-based controller

$$\hat{u} = -\hat{f} - \hat{f}_{wind} + \ddot{x}_d + \lambda \dot{\tilde{x}} \quad (13)$$

$$\dot{V}(t) = s\dot{s} = s(f - \hat{f}) + s(f_{wind} - \hat{f}_{wind}) + w(t) - k|s| \leq -\eta|s| \quad (14)$$

Wind estimation

Nonlinear Super-twisting Observer

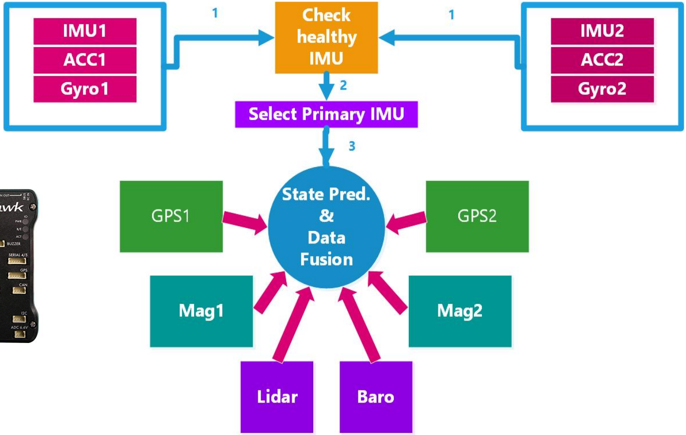
$$\begin{cases} \dot{z}_0 = v_0 + \frac{u_t}{m} u_x - K_p(\dot{x} - \dot{x}_d) \\ v_0 = -\alpha_{0x}|z_0 - \sigma|^{2/3} sgn(z_0 - \sigma) + z_1 \\ \dot{z}_1 = v_1, \;\; v_1 = -\alpha_{1x}|z_1 - v_0|^{1/2} sgn(z_1 - v_0) + z_2 \\ \dot{z}_2 = -\alpha_{2x} sgn(z_2 - v_1) \\ \hat{F}_x = z_1 \end{cases} \qquad (15)$$

[1] J. Davila, L. Fridman, and A. Levant," Second-order sliding-mode observer for mechanical systems," IEEE Transactions on Automatic Control, vol. 50, no. 11, Novembre 2005.

[2] Y. B. Shtessel, I. A. Shkolnikov, and A. Levant, "Smooth second-order sliding modes: Missile guidance application," Automatica, vol. 43, no.8, 2007.

Multi-sensor data fusion architecture

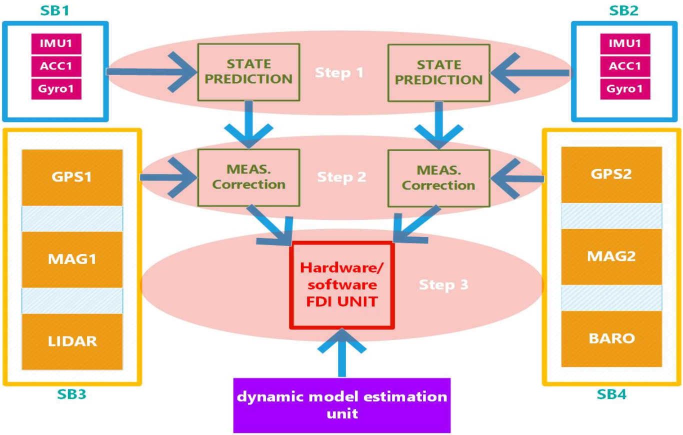
Arducopter EK2



Riseborough, Paul. "Application of data fusion to aerial robotics." Proc. of Embedded Linux Conference. 2015.

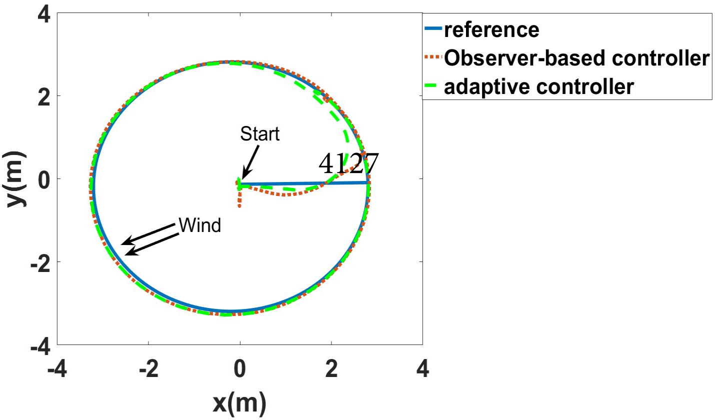
Multi-sensor data fusion architecture

Proposed architecture



Simulation - Adaptive Vs observer-based controller

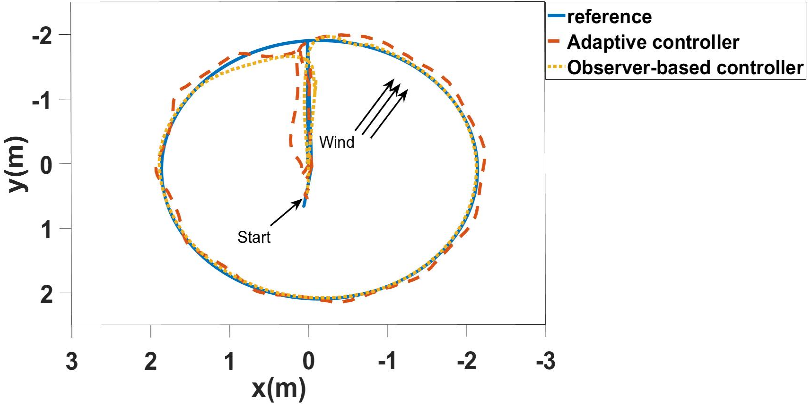
Small wind forces < 1 N



S. Rajappa, C. Masone, and P. Stegagno, "Adaptive super twisting controller for a quadrotor uav," IEEE International Conference on Robotics and Automation (ICRA), pp. 2971–2977,2016.

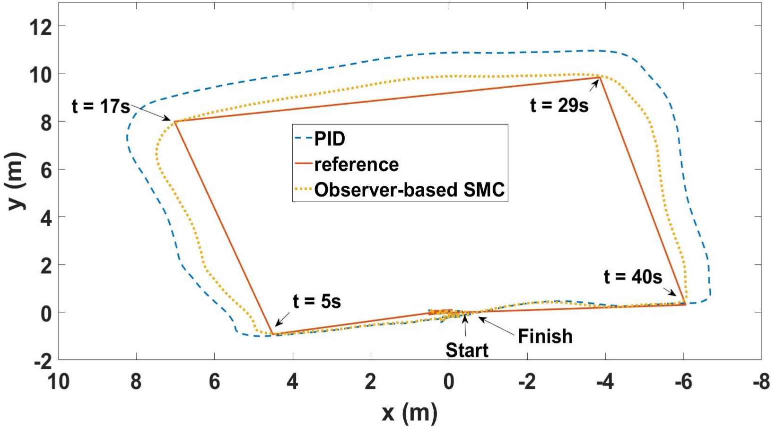
Simulation - Adaptive Vs observer-based controller

Wind forces ∽ 5-6 N

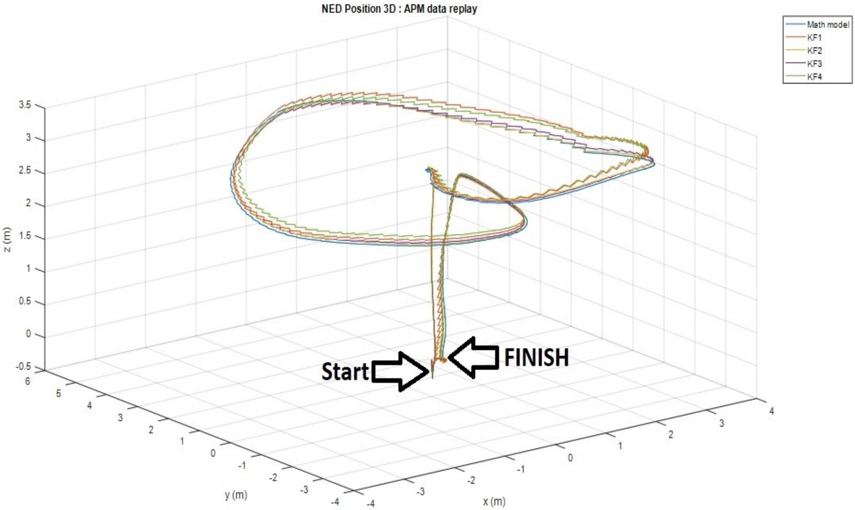


Experiment - PID Vs observer-based controller

Average wind forces ∽ 0.13 N



Simulation - Data fusion architecture



Video


Real flight Test of Observer-based
STA Controller Robust
to Wind Perturbation for
Multirotor UAV

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Thank You

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12 Octobre 2018

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