Closed-loop change detection for quadcopters

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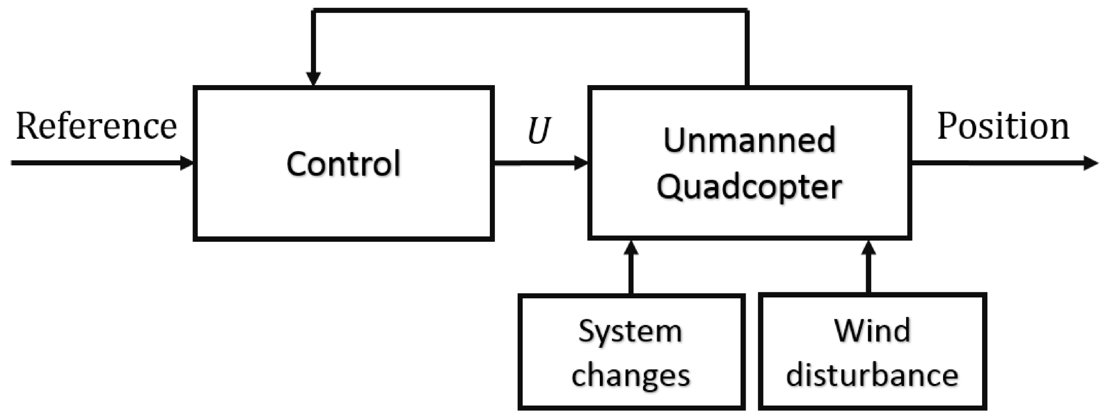
Summary

Change detection is important in many quadcopter applications. However, some model residuals can be misleading due to closed-loop control hiding system changes or significant effects of process disturbances. Here, it is shown that a sensor-to-sensor submodel can be used to detect a payload change based only on IMU measurements.

Quadcopter dynamics

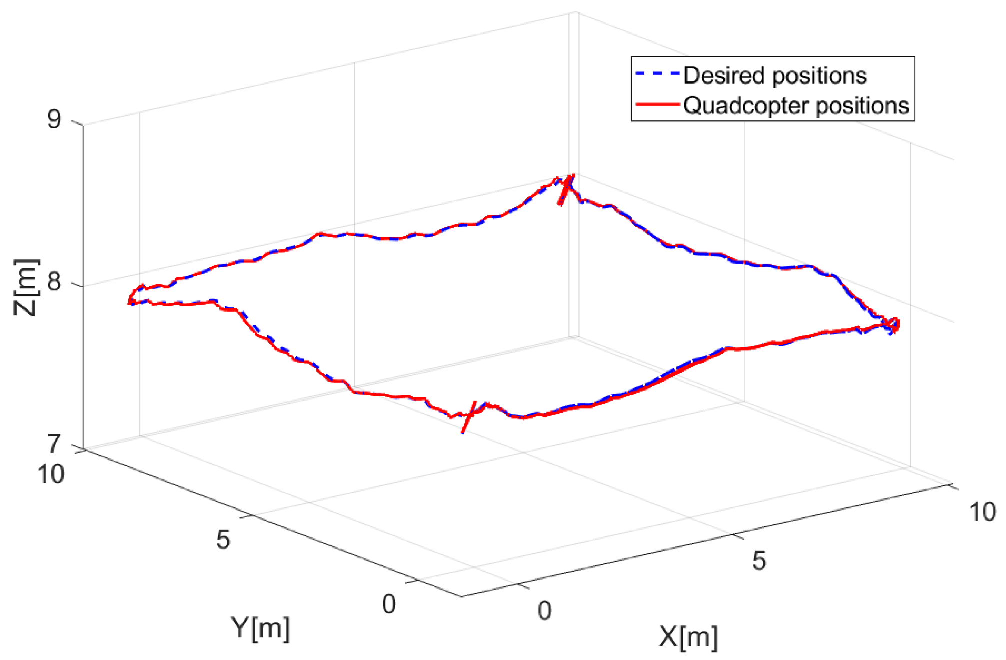


In the body-fixed frame, the dynamic equations of a rigid body quadcopter using the Newton-Euler equations are given by

$$\begin{aligned} m\dot{V}_B + m\nu \times V_b &= mR^T g + E_B^F(\Omega) + D_B^F(V_b) \\ I\dot{\nu} + \nu \times (I\nu) &= O_B^\tau(\nu, \Omega) + E_B^\tau(\Omega) \end{aligned} \tag{1}$$

where m is the mass of the quadcopter.

The wind turbulence can be modeled using the Dryden wind model. The controller reacts to the disturbances and drives the quadcopter to follow the desired path.



Sensor-to-sensor model[2]

Projecting (1) onto the $x-y$ plane in the body-fixed frame yields

$$\dot{u} = -g\sin\theta - \frac{\lambda_1}{m}u, \quad \dot{v} = g\cos\theta\sin\phi - \frac{\lambda_1}{m}v \tag{2}$$

where λ_1 is the drag coefficient. The IMU gives the roll rate p_m, pitch rate q_m and accelerations as

$$a_x = \frac{\lambda_1}{m}u + e_{a_x}, \quad a_y = \frac{\lambda_1}{m}v + e_{a_y} \tag{3}$$

The prediction errors of the linearized sensor-to-sensor model are

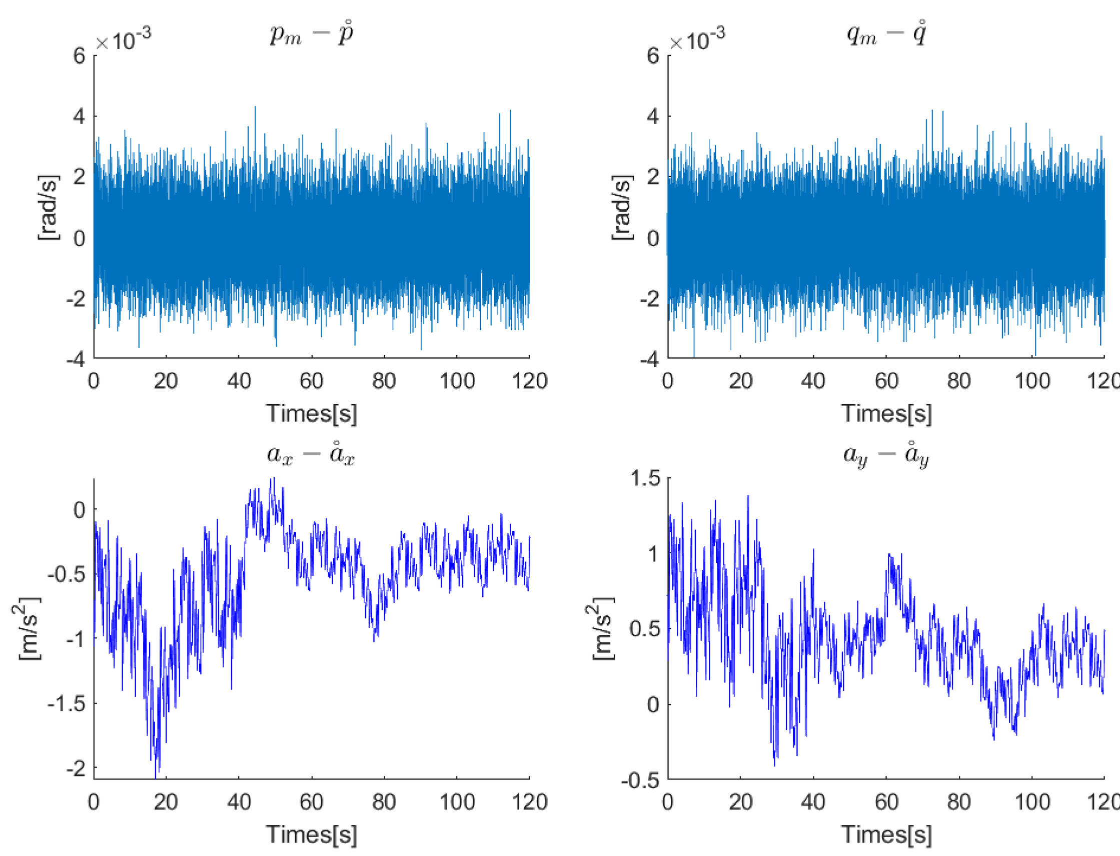
$$r_1(t) = a_x(t) - \varphi_x^T(t)\vartheta_x, \quad r_2(t) = a_y(t) - \varphi_y^T(t)\vartheta_y \tag{4}$$

where $\varphi_x^T(t) = [-a_x(t-1),\ -a_x(t-2),\ q_m(t-2)]$, $\varphi_y^T(t) = [-a_y(t-1),\ -a_y(t-2),\ p_m(t-2)]$ and $\vartheta_x = \vartheta_y = [-2 + \frac{\lambda_1}{m}T,\ 1 - \frac{\lambda_1}{m}T,\ \frac{\lambda_1}{m}gT^2]^T$.

Since the two submodels (4) have identical structures, only the pitch rate to the longitudinal acceleration model will be considered here.

Simulation result

A mass change at $t = 40s$ cannot be detected using the residuals between the measured and simulated signals p, q, a_x and a_y obtained from the 6 DOF nonlinear model since the effect can be mixed up with the wind.



Method

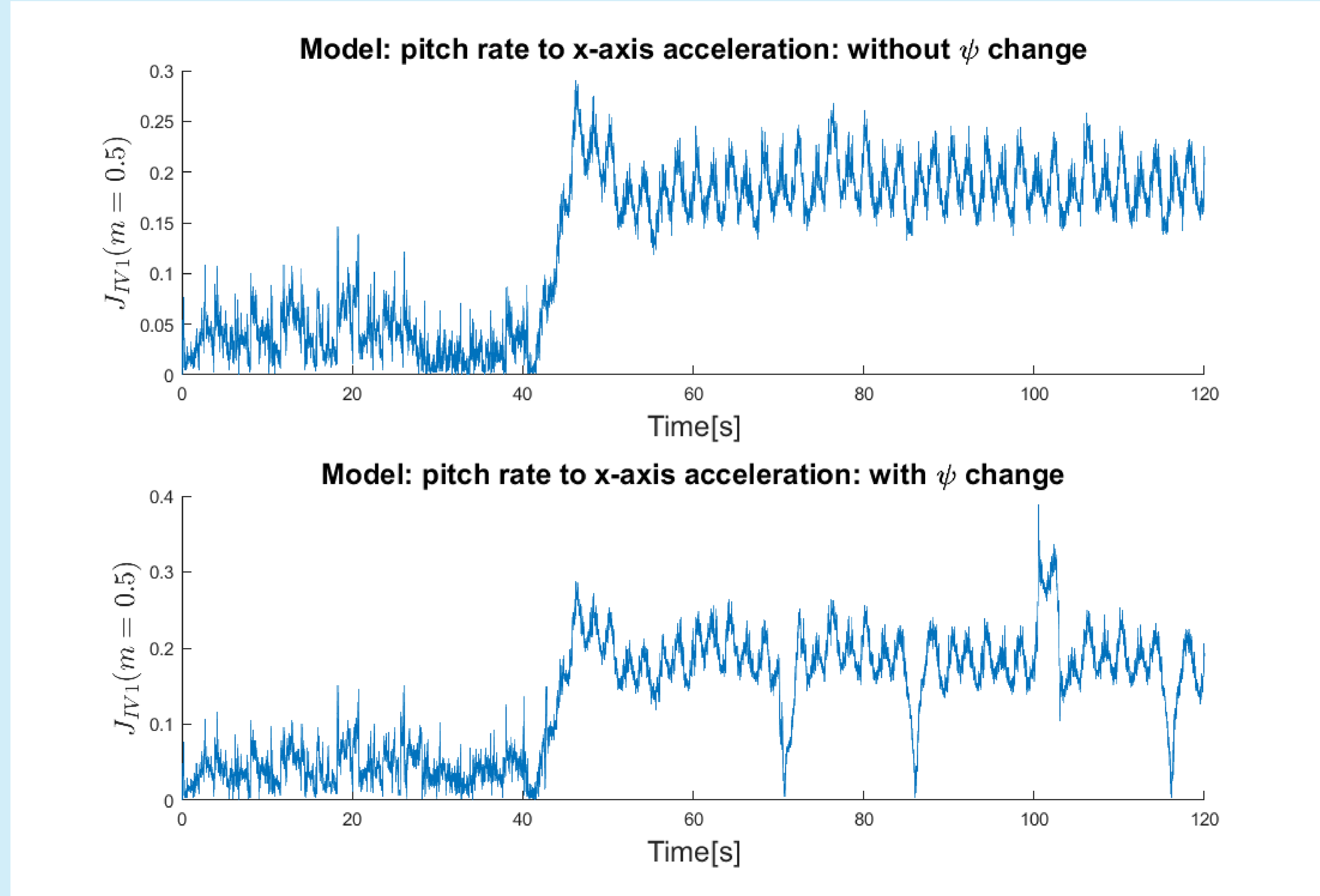
The IV cost function can be computed based on the sensor-to-sensor pitch rate longitudinal acceleration model as

$$J_{IV1}(t) = \Big\| \sum_{i=t-N_w+1}^{t} \lambda^{t-i} Z(i) r_1(i) \Big\|_2 \tag{5}$$

where λ is the forgetting factor. $Z(t) = [-\mathring{a}_x(t-1),\ -\mathring{a}_x(t-2),\ \mathring{q}(t-2)]^T$ where $\mathring{a}_x$ and $\mathring{q}$ are simulated signals from the reference. The residual $r_1(t)$ is computed using $m = 0.5kg$.

Detection result

Different flight conditions in terms of the wind turbulence and the course angle ψ of the quadcopter are investigated. The mass of the quadcopter increases linearly from $m = 0.5kg, \forall t \leq 40s$ to $m = 1kg, \forall t \geq 42s$.



The payload changes are detected using the IV cost function with and without course angle variation.

Papers

1. Ho, D., Hendeby, G., and Enqvist, M. Closed-loop change detection for quadcopters, to be submitted to the 21st IFAC World Congress in Berlin, Germany, 2020.
2. Ho, D., Linder, J., Hendeby, G., and Enqvist, M. Mass estimation of a quadcopter using IMU data, In *2017 International Conference on Unmanned Aircraft Systems*. Miami, Florida, USA.