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# Biomimetic Approach for Attitude Stabilization of a Flapping Micro Aerial Vehicle using Sensors Measurements

H. Rifai, J.-F. Guerrero-Castellanos, N. Marchand

## 1 Introduction

Inspired from the natural flight, the Flapping Micro Aerial Vehicles (FMAVs) have emerged recently as a challenging technology within flying robots. The sensory system of insects provides them with information about their position and orientation in the space besides interaction with their environment. For example, the halteres, sensors placed at the base of the wings, are used by insects to determine the angular velocity of their body. Other sensors like the sensilla, magnetic sense, ocelli, compound eyes, etc. help insects determine their position and orient their body relative to a fixed direction in the space. Some sensors models are presented in [2, 1] and their measurements are used to estimate the insect's attitude in [1] and to develop control laws using a linear quadratic optimal control in [3] or a proportional derivative output feedback in [5]. The main contribution of this work is the development of a control law aiming to stabilize the FMAV's attitude based directly on the measurement of some embedded sensors without the need of computing the orientation. The control torque is bounded allowing to take into account the amplitude bounds of the flapping wings and ensures the stability of the body.

## 2 Attitude stabilization

The technological equivalents of insects sensors, used in this work, are three rate gyros for the angular velocity measurement and a tri-axis accelerometer and a tri-axis magnetometer as reference sensors that give the measurement in their frame, of the gravity vector and magnetic field, fixed vectors in the space. Consider a reference sensor  $k \in \{1, \dots, n\}$  with  $n$  the number of embedded reference sensors. The current measurement of the sensor  $k$  in the FMAV's frame is denoted by  $s_k^b$  and the fixed vector in the space  $s_k^f$ . The error between the current and desired measurements is given by

$$\gamma = \frac{\Delta^{-1}}{n} \sum_{k=1}^n s_k^b \times R_d s_k^f \quad (1)$$

with  $\Delta = \text{diag}(\delta_1, \delta_2, \delta_3)$  is a scaling matrix such that  $\delta_j > 0$ ,  $R_d$  is the desired rotation matrix transforming the fixed frame to the FMAV's frame and  $\times$  is the vectorial product.

**Proposition 1** Denote by  $\omega = [\omega_1 \ \omega_2 \ \omega_3]$  the angular velocity of the FMAV's body measured by the three rate gyros,  $\gamma = [\gamma_1 \ \gamma_2 \ \gamma_3]$  the attitude error defined by (1) and

$\text{sat}_N(x) = \min(N, \max(-N, x))$  a saturation function between  $\pm N$ ,  $\min$  and  $\max$  are the classical minimum and maximum functions. Consider  $\lambda_j > 0$  and  $\rho_j > 0$ ,  $j \in \{1, 2, 3\}$ . The control torque defined by

$$\tau_j = -\text{sat}_{\bar{\tau}_j}(\lambda_j[\omega_j + \rho_j\gamma_j]) \quad (2)$$

with  $j \in \{1, 2, 3\}$ , stabilizes the FMAV's body at the equilibrium defined by  $(\omega, \gamma) = (0, 0)$ . The bound  $\bar{\tau}_j$  of the control torque component  $\tau_j$  is set such as  $\bar{\tau}_j \geq 3\lambda_j\rho_j$  and  $\delta_j = \lambda_j\rho_j$ .

The wings angles amplitudes that should be applied to the FMAV are then computed through a predefined mapping between the control roll and yaw torques  $(\tau_1, \tau_3)$  and the wings angles amplitudes. This mapping is effectively approximated by an ellipse, centered at the origin and defined by its semi-axis  $(a_r, b_r)$ . The pitch control torque  $\tau_2$  stabilizes the FMAV by means of a small mass moving inside its body. Insects adopte this technique by moving their legs in order to change their center of gravity.

### 3 Simulations

The FMAV is modeled as a rigid body subject to external aerodynamic forces and torques generated by the flapping wings.

The control torque (2) is applied to the FMAV using the tuning parameters as  $(\rho_1, \rho_2, \rho_3) = (20, 8, 100)$ ,  $(\lambda_1, \lambda_2, \lambda_3) = (\frac{7 \cdot 10^{-3} a_r}{3.1}, \frac{10^{-6}}{3.1}, \frac{10^{-2} b_r}{3.1 a_r} \sqrt{a_r^2 - \tau_1^2})$  and  $(\bar{\tau}_1, \bar{\tau}_2, \bar{\tau}_3) = (0.7 a_r, 10^{-5}, \frac{b_r}{a_r} \sqrt{a_r^2 - \tau_1^2})$  with  $(a_r, b_r) = (1.859 \cdot 10^{-5}, 5.843 \cdot 10^{-5})$ .

The evolution of the roll, pitch and yaw angles as well as the angular velocities measured by the rate gyros and the control torques are plotted in Fig 1. The stability is reached in a sufficiently fast time which makes the control law suitable for real-time implementation. Moreover, it is comparable to the values observed in true insects [4].

**Remark 1** *The roll, pitch and yaw angles are not used in the control computation; they are only depicted to show the stabilization of the FMAV.*

### 4 Conclusions and future works

The work proposed in this paper concerns the attitude stabilization of a FMAV by means of a control torque that uses direct sensors measurement without the computation of the bodies angles. Moreover, the control is bounded in order to take into account the bounds of the wings angles amplitudes. It is independent of the body's inertia and has a low computational cost.

Future works will consider the development of bounded control force aiming to control the MAV's trajectory based on sensor's measurements. In fact, insects can determine the sun direction using their ocelli. Moreover, the light polarization direction can be determined using the compound eyes. Based on polarized light compasses, for example, one can determine the direction of flight and couple it with the attitude control in order to ensure a flapping in the three-dimensional space.

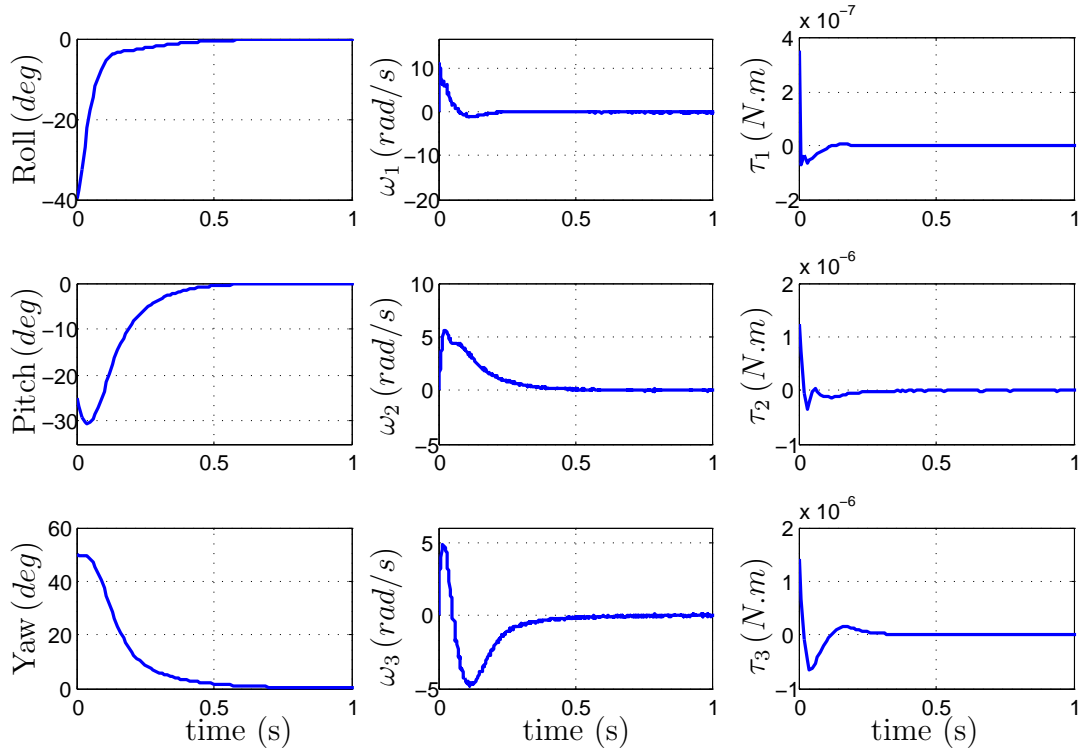


Figure 1: The attitude (left), angular velocity (middle) of the FMAV going from initial roll, pitch and yaw angles ( $-40^\circ$ ,  $-25^\circ$ ,  $50^\circ$ ) and null angular velocity and the control torques (right) applied to the FMAV.

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