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# Control Design for an Octorotor for Radar Applications

Maria Makarov, Cristina Stoica Maniu and Sihem Tebbani  
Laboratoire des Signaux et Systèmes  
CentraleSupélec-CNRS-Univ. Paris-Sud, Université Paris-Saclay,  
France, Gif-sur-Yvette F91192  
E-mail: {maria.makarov; cristina.stoica; sihem.tebbani}@centralesupelec.fr

Israel Hinostroza  
SONDRA Lab  
CentraleSupélec  
France, Gif-sur-Yvette F91192  
E-mail: israel.hinostroza@supelec.fr

**Abstract**—As part of a research and educational project, this paper proposes an  $H_\infty$  controller for an octorotor used for radar applications. In the context of a vertical take-off and landing multirotor with an embedded radar system, the  $H_\infty$  controller synthesis is developed based on a simplified linearized model and tested in simulation on the nonlinear model. A wind model, including turbulence and gust wind, has been considered in order to validate the robustness of the proposed controller.

## I. INTRODUCTION

In the last few years, the possibility to use small UAVs as platforms for radars has been substantially investigated [1], [2]. The objective of the present research and educational project is to design a VTOL (vertical take-off and landing) multirotor with an embedded radar system for civilian applications like crop field monitoring, damage evaluation after natural disasters, rescue operations after avalanches etc. In this context, a critical point that will affect the collected data is a stabilized attitude of the flying platform and its ability to precisely follow a prescribed trajectory, despite the possible wind disturbances.

A commercially available octorotor (ARF-MikroKopter OktoXL, MikroKopter, HiSystems GMBH) [3], [4] compatible with the required radar payload and the redundancy provided by the eight rotors, is considered in this paper. To meet the requirements of radar applications, the control system has to guarantee an efficient trajectory tracking, at a constant and relatively high speed [5], in spite of possible external wind disturbances [6]. Recently, various control schemes for attitude control or trajectory tracking have been presented for quadrotors [7], hexarotors [8] and octorotors [9], [10]. Among the linear control methods (see for example [11], [12] for reviews on the main control methods of multirotors),  $H_\infty$  control design methods are well adapted to solve the posed multivariable control problem with competing specifications on performance and robustness. The latter are especially important in presence of uncertainties [13] or external disturbances.

Using the model proposed in [5], this paper focuses on the  $H_\infty$  control design of the octorotor ARF-MikroKopter OktoXL. In order to increase the robustness of the controlled system, a keypoint consists in considering wind disturbances directly in the controller synthesis step. The octorotor with the thus designed multivariable controller is able to follow a

reference trajectory specified in terms of positions in space and the yaw angle. The inputs to the designed multivariable controller are the octorotor positions and attitude angles, and its outputs are the eight motors rotational speeds.

Section II is dedicated to the octorotor model analysis and the desired control specifications in view of radar applications. The  $H_\infty$  control design is presented in Section III. The proposed control law is validated through simulation results illustrated in Section IV. Finally, concluding remarks are drawn in Section V.

## II. SYSTEM DESCRIPTION AND CONTROL SPECIFICATIONS

The considered multirotor (Figure 1) has eight brushless motors with twin-bladed propellers, arranged in a star-shaped way. Longer arms of length  $L$  correspond to odd-numbered motors (providing higher torques) which rotate in the clockwise direction, whereas shorter arms of length  $l$  correspond to even-numbered motors (providing less momentum) which rotate in the opposite direction. Thus, this configuration improves the handling ability of the drone. Choosing opposite directions of rotation between the odd- and even-numbered motors is the solution to compensate the drag torque. The motors are fixed with a  $3^\circ$  inclination with respect to the vertical axis  $Z$ . The drone main parameters are provided in Table I.

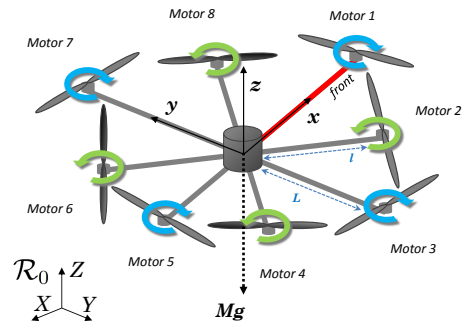


Figure 1: Considered octorotor and reference frames.

### A. Control requirements for radar applications

Synthetic Aperture Radar (SAR) image formation is based on the coherent sum of the scattered waves due to the periodic illumination of a scene by the radar [14]. For stripmap mode, sideway illumination (relative to the UAV movement) of the



The external inputs  $w = [w_1^T \ w_2^T \ w_3^T]^T$  contain the desired reference trajectories  $w_1 = [r_X \ r_Y \ r_Z \ r_\psi]^T \in \mathbb{R}^4$  to be followed by the variables  $X, Y, Z, \psi$ , the disturbances  $w_2 \in \mathbb{R}^3$  due to the wind and modeled as disturbances on the drone's velocities  $V_x, V_y, V_z$ , and the additional inputs  $w_3 \in \mathbb{R}^3$  used in the control design.

The controlled outputs  $z = [z_1^T \ z_2^T \ z_3^T]^T$  represent the filtered versions by respectively  $\mathbf{W}_1, \mathbf{W}_2, \mathbf{W}_5$  of the following signals: the errors  $\varepsilon \in \mathbb{R}^4$  on  $X, Y, Z, \psi$  with respect to the references, the control inputs  $u \in \mathbb{R}^8$ , and the additional controlled outputs  $z'_3 = [\varphi \ \theta \ V_x \ V_y \ \omega_x]^T$  used in the control design to emphasize their stabilization.

The controller inputs  $y = [y_1^T \ y_2^T]^T$  contain the errors  $y_1 = \varepsilon$  and the additional inputs  $y_2 = -v_{\varphi\theta\psi} = -[\varphi \ \theta \ \psi]^T$  which are affected by additional fictitious inputs  $w'_3$  during the design phase. The controller outputs  $u = [\Omega_1 \ \Omega_2 \ \Omega_3 \ \Omega_4 \ \Omega_5 \ \Omega_6 \ \Omega_7 \ \Omega_8]^T \in \mathbb{R}^8$  are the motor rotation speeds.

According to these notations and to the control design structure summarized in Figure 3, the closed-loop transfer matrix between the external inputs  $w$  and controlled outputs  $z$  in the  $H_\infty$  problem (11) is expressed as follows:

$$z = LFT(P, K)w \quad (12)$$

$$\begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} = \begin{bmatrix} \mathbf{W}_1 T_{r \rightarrow \varepsilon} & \mathbf{W}_1 T_{w'_2 \rightarrow \varepsilon} \mathbf{W}_3 & \mathbf{W}_1 T_{w'_3 \rightarrow \varepsilon} \mathbf{W}_4 \\ \mathbf{W}_2 T_{r \rightarrow u} & \mathbf{W}_2 T_{w'_2 \rightarrow u} \mathbf{W}_3 & \mathbf{W}_2 T_{w'_3 \rightarrow u} \mathbf{W}_4 \\ \mathbf{W}_5 T_{r \rightarrow z'_3} & \mathbf{W}_5 T_{w'_2 \rightarrow z'_3} \mathbf{W}_3 & \mathbf{W}_5 T_{w'_3 \rightarrow z'_3} \mathbf{W}_4 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix}$$

where  $T_{a \rightarrow b}$  denotes the transfer matrix from the input  $a$  to the output  $b$ .

The weighting functions  $\mathbf{W}_1, \mathbf{W}_2, \mathbf{W}_3, \mathbf{W}_4, \mathbf{W}_5$  are used as the tuning parameters in the proposed design. As in a classical four-block  $H_\infty$  control design,  $\mathbf{W}_1, \mathbf{W}_2, \mathbf{W}_3$  are used to shape respectively the sensitivity function  $\mathbf{S} \stackrel{def}{=} T_{r \rightarrow \varepsilon}$  (which influences the response to the reference), the transfer  $\mathbf{KS} \stackrel{def}{=} T_{r \rightarrow u}$  (which influences the control signal) and the transfer  $\mathbf{SG} \stackrel{def}{=} T_{w'_2 \rightarrow \varepsilon}$  (which influences the response to the disturbances). Once  $\mathbf{W}_1, \mathbf{W}_2, \mathbf{W}_3$  are fixed, the weighting on the transfer  $\mathbf{KSG} \stackrel{def}{=} T_{w'_2 \rightarrow u}$  is fixed too. Moreover,  $\mathbf{W}_4$  is used to tune the influence of the input  $v_{\varphi\theta\psi}$  with respect to  $y_1$  in the controller. Finally,  $\mathbf{W}_5$  is used to weight the importance of the additional controlled outputs  $z'_3$ .

The weighting functions  $\mathbf{W}_1, \mathbf{W}_2, \mathbf{W}_3$  are chosen as first order filters with stable inverses and are represented in Figure 4.  $\mathbf{W}_4$  and  $\mathbf{W}_5$  are fixed to 1. The design problem is solved by Linear Matrix Inequalities (LMI) method using Matlab `hinfsyn` function. The obtained controller is of order 25, and has 7 inputs and 8 outputs. The maximum singular values of the corresponding closed-loop transfer matrices with the obtained controller ( $\gamma = 3$ ) are represented in Figure 4 and fulfill the specifications.

#### IV. SIMULATION RESULTS

The previously designed controller has been reduced to the order 15, and then evaluated in simulation with the complete nonlinear model. The simulation corresponds to the case study for radar applications described in Section II-A.

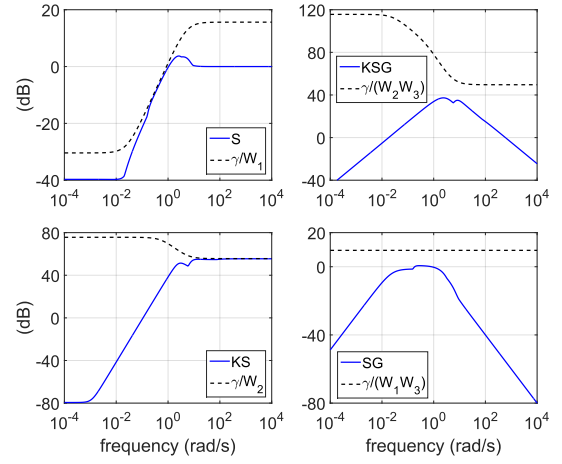


Figure 4: Maximum singular values of closed-loop transfer matrices and corresponding weighting functions.

The trajectory reference corresponds first to a take-off until an altitude of 100 m is reached, followed by a translation on the  $X$ -axis at a constant speed of 10 m/s (Figure 5). Robustness to the wind disturbances is evaluated by applying wind turbulence and wind gusts of 10 km/h in the  $-X$  direction, and 20 km/h in the  $-Y$  direction (Figure 5). The specifications in Table II are fulfilled: in presence of wind disturbances, the errors on the trajectory are within  $\pm 1$  m on  $X$  and  $Y$  (Figure 6), and the speed variations are within  $\pm 0.2$  m/s (Figure 7). The angles are stabilized which can allow an efficient post-treatment of the acquired radar data (Figure 8). Finally, the control signals are sufficiently smooth and within allowed control amplitudes (Figure 9).

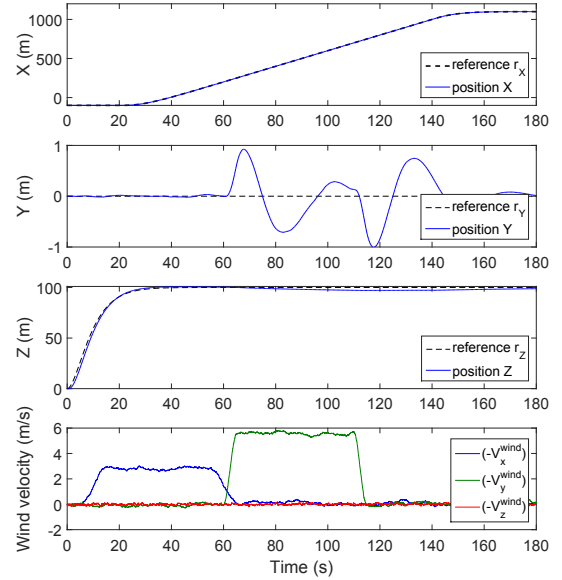


Figure 5: Positions  $X, Y, Z$  and wind disturbance profile.

#### V. CONCLUSION

In the context of an educational project, this paper proposes an  $H_\infty$  control design of an octorotor for radar applications.

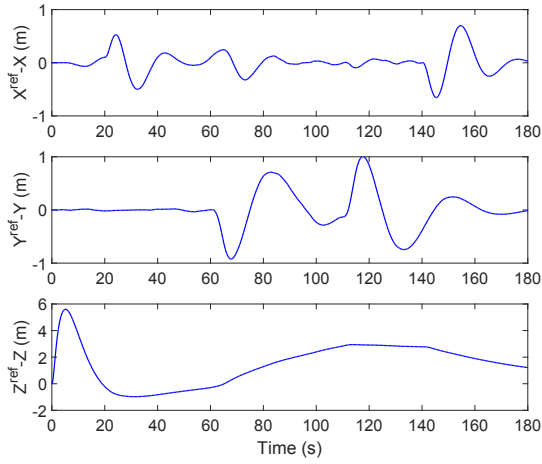


Figure 6: Errors on  $X, Y, Z$ .

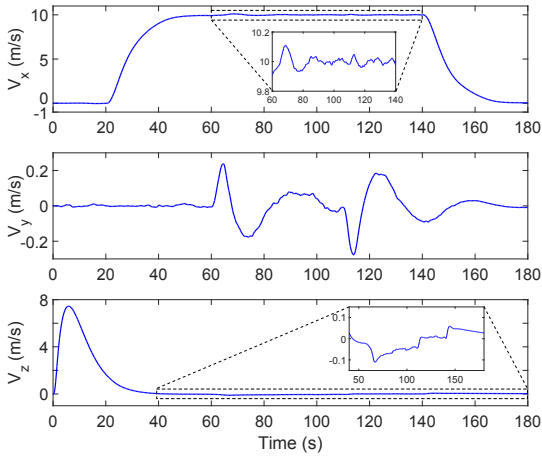


Figure 7: Speeds  $V_x, V_y, V_z$ .

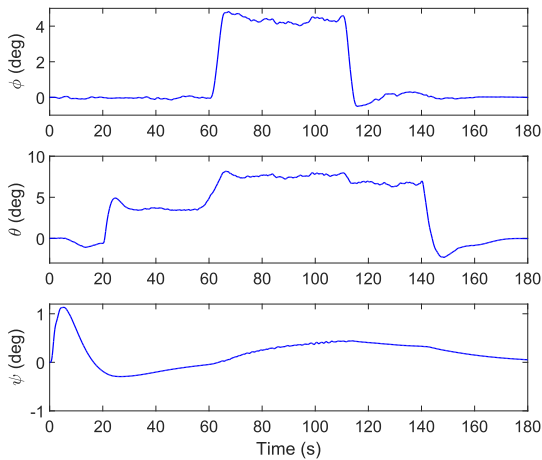


Figure 8: Angles  $\varphi, \theta, \psi$ .

A linearized model is used for the controller synthesis. The proposed control law is validated on the complete nonlinear model in a windy scenario. Current work focuses on the comparison with different control laws and on the implementation on the real drone.

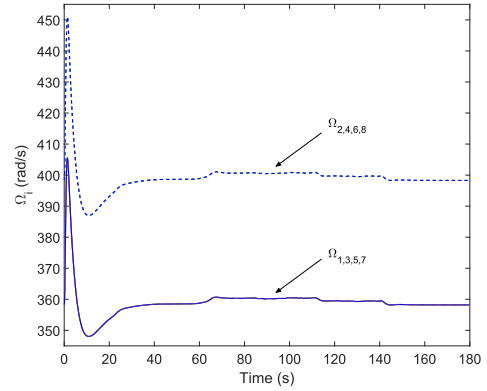


Figure 9: Control inputs - motor speeds  $\Omega_i$  (odd numbered - solid line, even numbered - dotted line).

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