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A Controller Based on PVTOL Control Signals for Guiding a Quadrotor in 3D Navigation Tasks

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Abstract— **In this work a novel control architecture is proposed to guide an Unmanned Aerial Vehicle (UAV), specifically a quadrotor, in 3D flights correspondent to positioning and path-following tasks. Such an architecture is based on the fusion of three control signals generated by three simpler controllers (associated to PVTOL tasks). Considering the whole navigation as a task composed by the control of the vehicle orientation with respect to its target (associated to a Z-PVTOL controller), the control of its forward movement (associated to a XZ-PVTOL controller), and the correction of any side displacement (associated to a YZ-PVTOL controller, similar to the XZ-PVTOL controller), a first approach was to execute such partial maneuvers one each time, using the same three PVTOL controllers here adopted, switching from one to other of these controllers according to a supervisor. The new approach adopted in this paper corresponds to consider that the three PVTOL controllers act simultaneously, and generating the final control signal to be sent to the UAV through fusing the individual control signals generated by the PVTOL controllers, thus smoothly coupling three simpler controllers. Experimental results are presented to validate the proposed approach, and the performance of the controller thus designed is compared to the one correspondent to the switching approach.**

I. INTRODUCTION

The interest of the research community in unmanned aerial vehicles (UAVs) has grown in the latest years, mainly regarding autonomous flight missions. Such an interest is due to some characteristics of these aircrafts, which make easier to accomplish tasks in several areas, like public security (e.g. aerial space or urban traffic supervision), natural risk management (e.g. monitoring of active volcanoes), environmental management (e.g. air pollution measurement and forest monitoring), intervention in hostile environments (e.g. radioactive atmospheres), infrastructure maintenance (e.g. inspection of electrical power lines and water or oil pipelines), and precision agriculture (e.g. detection and treatment of infested plantations), amongst others. In these kinds of application the use of UAVs is much more advantageous than the use of unmanned ground vehicles (UGVs), due to their tridimensional mobility [1]–[4].

Applications like those aforementioned demand the capabilities of flying in low altitudes, hovering and vertical taking off and landing (VTOL capability), for instance. Therefore, small autonomous rotary wing aircrafts (RUAS, or rotorcraft unmanned aircraft systems) are more suitable for such applications than autonomous fixed wing aircrafts [5]. Indeed, a crucial characteristic of a helicopter and similar vehicles, like a quadrotor, is that they can be controlled in the lateral, longitudinal and vertical directions, with any orientation. Moreover, a RUAS can also be controlled to hover over any desired point, with any orientation. Such characteristics give a RUAS much more maneuverability, which distinguishes them from fixed wing aircrafts [6]. A disadvantage, however, is the greater energy consumption during a flight, what causes that in general the flights with small helicopters and quadrotors are short-time flights.

Dealing specifically with RUAS, a quadrotor, for instance, or similar vehicles, is much simpler to build and control than the classic helicopter. The reason is that they do not demand the mechanical subsystem called swashplate. Moreover, they are controlled just varying the rotation of each one of their four motors, which rotate in opposite direction in pairs, making the quadrotors very attractive platforms to test control strategies. In this work, in particular, the quadrotor *AR.Drone*® 2.0, from Parrot Inc., illustrated in Figure 1, is the platform adopted to run the experiments to validate the proposed control architecture.

RUAS control has gain the attention of several researchers, from both control and robotics communities, due to the challenges and opportunities of designing and experimenting new control strategies. In fact, a lot of papers about RUAS control is yet available in the literature. Some of them are based on adaptive control, such as [7], where the authors propose a nonlinear adaptive control for autonomously fly a quadrotor based on visual information. Other works use the technique of backstepping, like the one reported in [8]. By its turn, in [9] the proposed algorithm generates optimal trajectories using a sequence of 3D positions and yaw angles. Such trajectories are then followed with precision using a nonlinear controller with inner and outer loops. Another example is [10], where a real-time control scheme with saturation is proposed, based on the Lyapunov stability criterion. Other examples are [11] and [12], where a high-level

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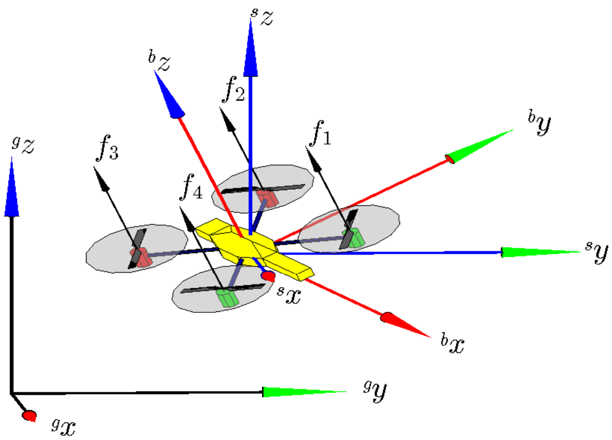


Fig. 1. Model of 6 DOF of the quadrotor *AR.Drone*® 2.0, showing the coordinate frames associated to it and its abstract control inputs $f_i, i = 1, \cdots, 4$. The inertial, spacial and body coordinate frames are $\langle g\rangle$, $\langle s\rangle$ and $\langle b\rangle$, indicated by the superscript indexes at the left in the axes x, y and z.

nonlinear under-actuated controller is developed and tested. Also deserving mention, one has [13], where the authors compare the performance of their nonlinear controller to the performance of a linear controller, specifically a linear quadratic regulator (LQR), which presents stability problems when the system operates far from the operating point used in the design of the linear controller. As a result, it is well established in the literature that nonlinear controllers are more effective in controlling RUAS.

A common detail of the above mentioned works, as well as one can notice in several other works, is that they are based on the nonlinear model of the vehicle, what many times make difficult to implement the designed control laws, either due to the high computational burden correspondent to the algorithm or because the degree of idealism of the model is so high that it is not possible to experiment the controller thus designed out of the lab. An alternative was presented in [14], where the concept of PVTOL tasks is introduced, which correspond to flights restricted to a vertical plane, such as the XZ or the YZ planes of the cartesian space, or even to a translation along the X axis and a rotation around it (a VTOL task, a more particular case). This means that the vehicle lifts and orientates itself, pointing its own X axis to the desired target (a VTOL task), before moving forward towards the target (a PVTOL maneuver correspondent to the XZ plane), stopping there and landing (another VTOL task). Nowadays PVTOL tasks have become important benchmarks for control designs, having as objectives to stabilize and move a RUAS in a vertical plane or in a vertical line. Regarding the conventional RUAS, which have 6 degrees of freedom, this can be achieved by restricting some of their degrees of freedom. Depending on the degrees of freedom that are restricted different PVTOL tasks are accomplished. If the task to be accomplished is to navigate in the XZ plane, for instance, the yaw and roll angles should be restricted to be zero (see [15]). To move only in the YZ plane, the yaw and pitch angles are those which should be kept in zero all the time, whereas for hovering (a VTOL task) the lateral and longitudinal displacements should be null (what means to keep the roll and pitch angles in zero). These three PVTOL tasks are illustrated in Figure 2.

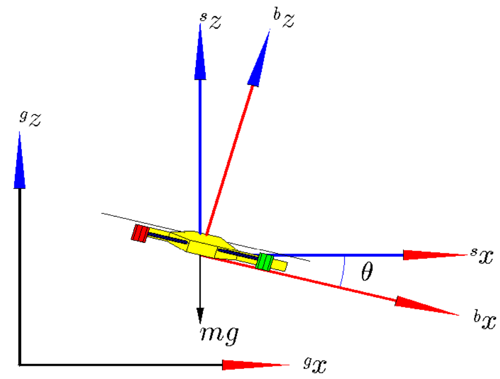
An important aspect regarding the PVTOL/VTOL tasks is that no limitation is imposed to its operating point, differently of what occurs in the cases of linearization. This means that even for PVTOL/VTOL tasks nonlinear controllers have better performance in comparison to linear controllers based on linearized models, as it occurs in the cases of tasks that take into account all the degrees of freedom of the vehicle.

In this context, this work deals with the control of a rotary wing UAV combining different PVTOL controllers to guide a quadrotor to a desired 3D position, with each one of the 2D or 1D controllers based on the theory of Lyapunov. Moreover, one can specify a sequence of points to be reached by the UAV, what corresponds to a path-following task. Therefore, the proposed controller is suitable for accomplishing positioning and path-following tasks. However, the combination of the PVTOL controllers here considered is quite different of the one dealt with in [16]: there the PVTOL controllers are combined through switching, whereas in this work such a combination corresponds to the fusion of the control signals generated by each one of the three PVTOL controllers. This means that in this work all the three PVTOL controllers are active all the flight, what is not the case when switching from one to other. The reason for developing this strategy is that the switching between the PVTOL controllers takes much more time to accomplish the task, what makes not feasible to use such control scheme in trajectory-tracking tasks, for instance, in which velocity requisites are imposed by the trajectory being tracked. The expectation was that the scheme based on the fusion of the control signals generated by the three PVTOL controllers would be much faster, what really happens, as it will be shown ahead in this text.

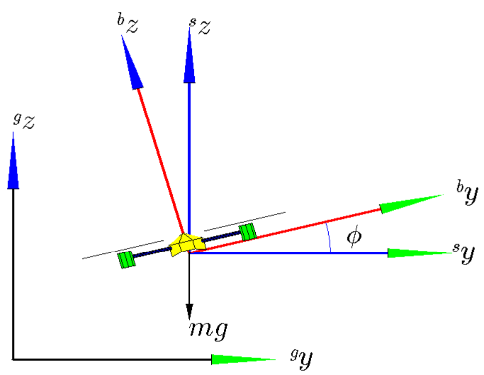
To address the topics mentioned so far, the paper is hereinafter split in the following sections: Section II, which briefly describes the three PVTOL controllers adopted, Section III, which describes the fusion engine used to combine the control signals delivered by the three PVTOL controllers to generate the final control signal to be applied to the quadrotor, Section IV, which discusses some experiments run using the proposed control architecture, and, finally, Section V, which presents the main conclusions of the work.

II. PVTOL Controllers Adopted

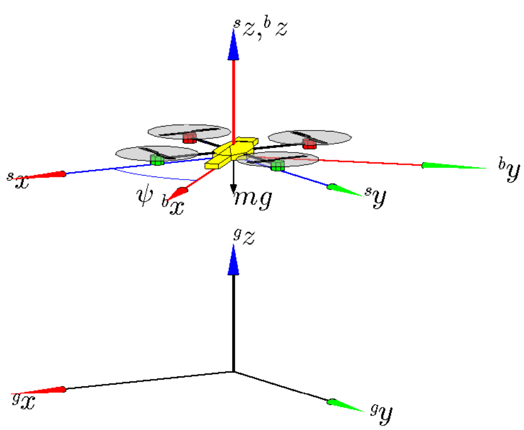
As it has already been mentioned, three controllers designed to guide the UAV in accomplishing PVTOL tasks have been implemented, and the control signals they generate are inputted to a decentralized [17]–[19], the data fusion engine selected. This way a single control signal is generated, which will be sent to the quadrotor to guide it from its current position to a desired one, thus accomplishing a 3D positioning task. The essence of this approach is that controllers for bidimensional movement (PVTOL controllers) are used to guide the 3D navigation taking advantage of their simpler



(a) Characterization of the PVTOL task in the XZ plane.



(b) Characterization of the PVTOL task in the YZ plane.



(c) Characterization of the VTOL task in the Z axis.

Fig. 2. Characterization of the PVTOL and VTOL tasks for the quadrotor *AR.Drone*® 2.0.

design, tuning and implementation (what is meaningful when thinking on running the 3D controller onboard the UAV).

The first one of such controllers is a controller for the ascending/descending movement and orientation. Such a controller is responsible for the linear displacement along the Z axis and the rotation around it (yaw movement), and is hereinafter referred to as the Z-VTOL controller. To implement it the pitch and roll angles are restricted to be zero along all the navigation, for the quadrotor. This means that the designed controller keeps the correspondent control variables null, letting the internal autopilot responsible for stabilizing such variables in the desired values. Notice, therefore, that such a controller is suitable only for quadrotors with internal autopilot, such as the *AR.Drone*®2.0 quadrotor used in this work. As for the second PVTOL controller, its objective is to allow the quadrotor to move upwards/downwards and ahead/behind, corresponding to a XZ-PVTOL controller. This means that the roll and yaw angles should remain null along the navigation (again, this is possible only when an internal autopilot is available). Finally, in the case of the third PVTOL controller the desired movement is similar to the second case, with the difference that now the null angles are the pitch and yaw ones, thus configuring a YZ-PVTOL controller. Thus, one has the VTOL movement only in the Z direction with rotation around it, a PVTOL movement in the XZ plane and a PVTOL movement in the YZ plane, which are characterized in Figure 2. Such controllers are discussed in details in [16] and [15], so that they will not detailed here.

Finally, it should be mentioned that the proposal of using a 3D controller based on the switching between the three PVTOL controllers above, proposal originally presented in [16], is also implemented here, for the sake of comparing the performance of the proposal presented here against the performance of the switching approach.

III. Fusion of the PVTOL Controllers

To perform the data fusion one can use two methods, the Kalman filter [20], [21] and the information filter [22]. Such filters allow fusing data provided by multiple sensors/systems, resulting in output data with a variance that is lower than the lowest variance associated to the input data series [17].

As for the information filter, it is essentially the Kalman filter with the equations written as function of the information about measures of the states of interest [18], not as a function of the estimates of such states and the covariances associated to them [17]. In this work the information filter, in its decentralized version, was adopted as the data fusion engine, for presenting the advantages, compared to the decentralized Kalman filter, that its equations are simpler to implement and its robustness in terms of initialization. Indeed, to initialize the decentralized information filter it is enough to consider a state information vector (y) equal to zero and an information matrix (Y) close to zero, however not null, whereas in the case of the Kalman filter it is necessary a previous knowledge of the system to have a good initial estimate of the state vector and the matrix of error covariance.

A. *Information filter*

The equations of the information filter are based on

$$Y_{(k)} = P^{-1}_{(k|k-1)} \tag{1}$$

and

$$\hat{y}_{(k)} = P^{-1}_{(k|k-1)}\hat{x}_{(k|k-1)} = Y_{(k)}\hat{x}_{(k|k-1)}, \quad (2)$$

which correspond, respectively, to the matrix of information and the vector of state information.

Adopting such values, the equations correspondent to the filter itself are

Prediction:

$$\begin{aligned} \hat{y}_{(k|k-1)} &= L_{(k)}\hat{y}_{(k-1|k-1)} \\ Y_{(k|k-1)} &= \left[A_{(k)}Y^{-1}_{(k-1Zk-1)}A^{T}_{(k)} + Q_{(k)}\right]^{-1} \end{aligned} \quad (3)$$

Estimation:

$$\begin{aligned} \hat{y}_{(k|k)} &= \hat{y}_{(k|k-1)} + i_{(k)} \\ Y_{(k|k)} &= Y_{(k|k-1)} + I_{(k)}, \end{aligned} \quad (4)$$

where

$$L_{(k)} = Y_{(k|k)}A(k)Y^{-1}_{(k|k-1)} \quad (5)$$

$$i_{(k)} = H^{t}_{(k)}R^{-1}_{(k)}z_{(k)} \quad (6)$$

$$I_{(k)} = H^{t}_{(k)}R^{-1}_{(k)}H_{(k)} \quad (7)$$

are, respectively, the coefficient of information propagation, the contribution of the state information, and the information matrix, all associated to each state.

B. Decentralized information filter

As the information filter is a derivation of the Kalman filter, the formulation of the decentralized information filter is similar to the one of the decentralized Kalman filter. Thus, for the *i*-th local filter one has

$$\hat{y}_{i(k)} = \hat{y}_{(k|k-1)} + i_{i(k)} \quad (8)$$

$$Y_{i(k)} = Y_{(k|k-1)} + I_{i(k)}, \quad (9)$$

whereas for the global filter one has

$$\hat{y}_{(k)} = \sum_{i}^{n}\hat{y}_{i(k)} - (n-1)\hat{y}_{(k|k-1)} \quad (10)$$

$$Y_{(k)} = \sum_{i}^{n}Y_{i(k)} - (n-1)Y_{(k|k-1)}. \quad (11)$$

Figure 3 illustrates the diagram correspondent to a generic decentralized information filter having i local information filters.

C. The proposed control architecture

The control architecture here proposed corresponds to a decentralized information filter with three local filters, each one receiving the control signal generated by one of the three PVTOL controllers mentioned in Section II. It is depicted in Figure 4, where on can see that each one of the three PVTOL controllers receives information from the UAV and calculates the correspondent control signal, which is delivered to the correspondent local information filter, which, by their turn, deliver the information to the global information filter, what corresponds to a recursive and optimized data fusion method [17], [18].

The most important aspect, regarding the proposed approach, is how to select the weight associated to each local filter to guide the UAV to accomplish its positioning or path-following task. As the fusion of the available control signals is a kind of weighted average, such selection is a key aspect of the architecture. In short, the proposed control architecture determines the matrix of error covariance for the errors in the observations (control signals delivered by the XZ-PVTOL, YZ-PVTOL and Z-PVTOL controllers) with weights calculated from the errors in the position and velocity of the UAV. In principle, the proposed method is an evolution of the switching control architecture: instead of the switching between the individual controllers a fraction of each of such controllers is used according the covariance associated to them. This way the control signals provided by the PVTOL controllers, which are simpler to design, implement and tune, are combined to solve more complex tasks.

D. Estimating the control signals for the UAV

The output variables of each individual controller are

$$\hat{\mathbf{x}}_i = [u_\theta \ u_\phi \ u_{\dot{\psi}} \ u_{\dot{z}}], \quad (12)$$

where i stands for the i-th controller, $u_{\dot{z}}$ represents a linear velocity command causing displacement along the axis z_w, $u_{\dot{\psi}}$ represents an angular velocity command causing the rotation around the axis z_w, u_ϕ represents, indirectly, a linear velocity command causing displacement y_b (indirectly because performed through the roll angle ϕ), and, finally, u_θ represents, also indirectly, through the pitch angle θ, a linear velocity command causing displacement in the axis x_b.

As mentioned before, the input data for estimating the final control signal to be sent to the UAV are the instantaneous values of the individual control signals generated by the controllers XZ-PVTOL (correspondent to the first local filter, for which $i=1$), YZ-PVTOL $(i=2)$ and Z-PVTOL $(i=3)$. Therefore, the global filter has three local filters connected to it, and for a generic local filter the configuration of the measure vector, observation model and covariance matrix of the measurement error are

$$\begin{aligned} \mathbf{z}_i &= [u_\theta \ u_\phi \ u_{\dot{\psi}} \ u_{\dot{z}}], \\ \mathbf{H}_i &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \text{and} \\ \mathbf{R}_i &= \begin{bmatrix} \sigma^2_{ix} & 0 & 0 & 0 \\ 0 & \sigma^2_{iy} & 0 & 0 \\ 0 & 0 & \sigma^2_{i\psi} & 0 \\ 0 & 0 & 0 & \sigma^2_{iz} \end{bmatrix}. \end{aligned} \quad (13)$$

When regarding the particularities of the PVTOL controllers, the three configurations are

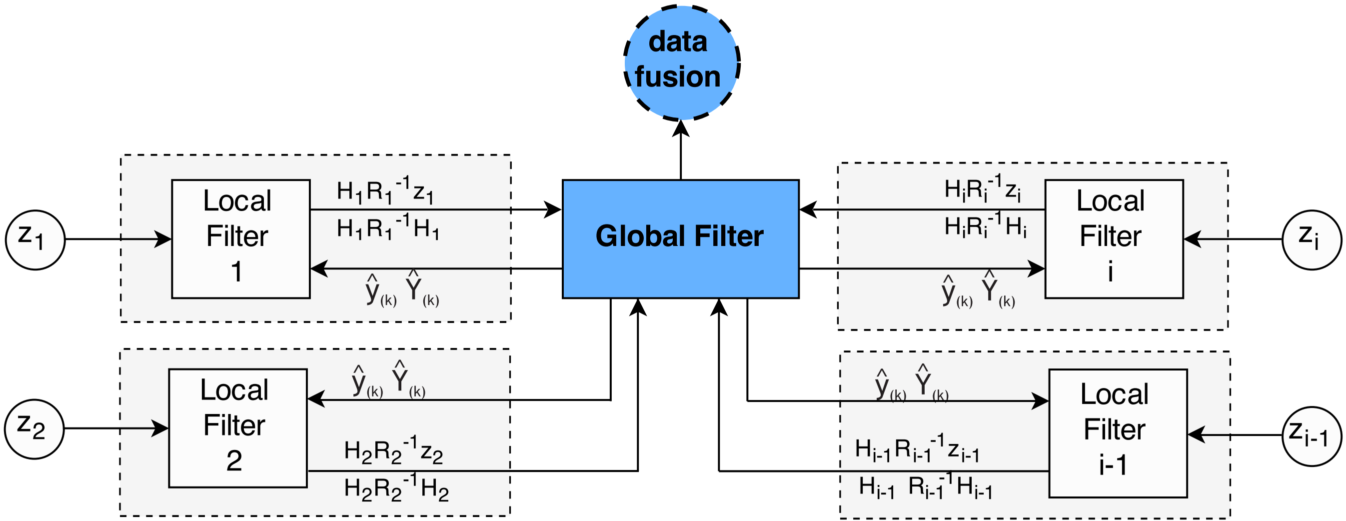


Fig. 3. Diagram correspondent to the decentralized information filter with i local information filters. H,R and z are the observation model, the estimate of the noise covariance and the vector of measurements, respectively.

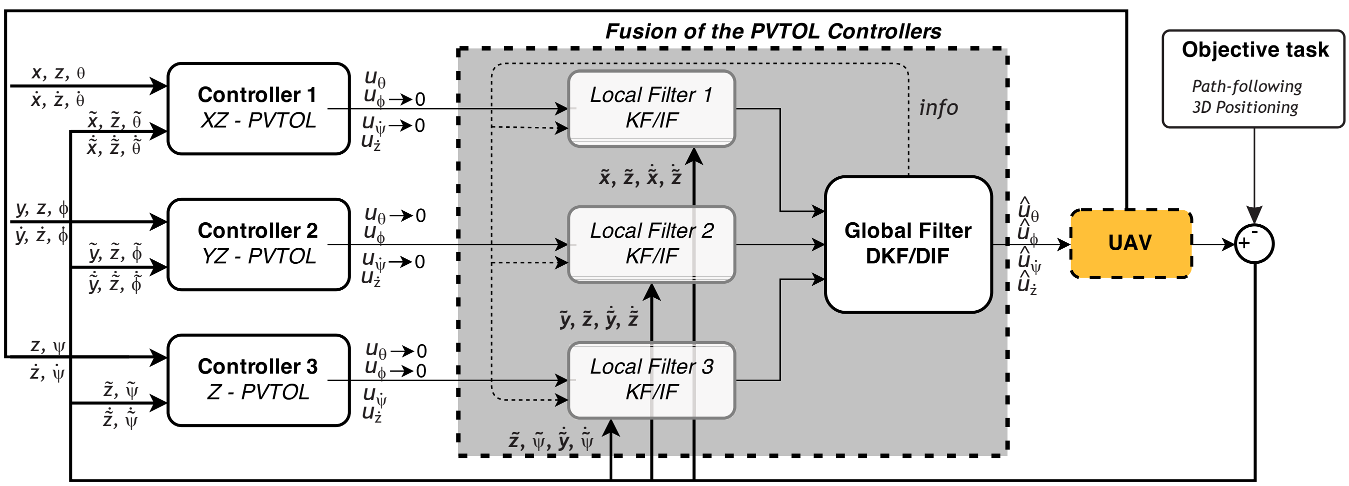


Fig. 4. Proposed control architecture. In the fusion block $info$ corresponds to $\hat{y}_{(k)}, \hat{Y}_{(k)}$.

- Filter 1 (associated to the XZ-PVTOL controller):

$$\mathbf{z}_1 = [u_\theta \; \overbrace{u_\phi}^{0} \; \overbrace{u_\psi}^{0} \; u_{\dot{z}}], \quad \text{and}$$

$$\mathbf{R}_1 = \begin{bmatrix} \frac{1}{\sigma(\tilde{x},\dot{\tilde{x}})} & 0 & 0 & 0 \\ 0 & \sigma(\tilde{y},\dot{\tilde{y}}) & 0 & 0 \\ 0 & 0 & \sigma(\tilde{\psi},\dot{\tilde{\psi}}) & 0 \\ 0 & 0 & 0 & \frac{1}{\sigma(\tilde{z},\dot{\tilde{z}})} \end{bmatrix}; \quad (14)$$

- Filter 2 (associated to the YZ-PVTOL controller):

$$\mathbf{z}_2 = [\overbrace{u_\theta}^{0} \; u_\phi \; \overbrace{u_\psi}^{0} \; u_{\dot{z}}], \quad \text{and}$$

$$\mathbf{R}_2 = \begin{bmatrix} \sigma(\tilde{x},\dot{\tilde{x}}) & 0 & 0 & 0 \\ 0 & \frac{1}{\sigma(\tilde{y},\dot{\tilde{y}})} & 0 & 0 \\ 0 & 0 & \sigma(\tilde{\psi},\dot{\tilde{\psi}}) & 0 \\ 0 & 0 & 0 & \frac{1}{\sigma(\tilde{z},\dot{\tilde{z}})} \end{bmatrix}; \quad (15)$$

- Filter 3 (associated to the Z-PVTOL controller):

$$\mathbf{z}_3 = [\overbrace{u_\theta}^{0} \; \overbrace{u_\phi}^{0} \; u_\psi \; u_{\dot{z}}], \quad \text{and}$$

$$\mathbf{R}_3 = \begin{bmatrix} \sigma(\tilde{x},\dot{\tilde{x}}) & 0 & 0 & 0 \\ 0 & \sigma(\tilde{y},\dot{\tilde{y}}) & 0 & 0 \\ 0 & 0 & \frac{1}{\sigma(\tilde{\psi},\dot{\tilde{\psi}})} & 0 \\ 0 & 0 & 0 & \frac{1}{\sigma(\tilde{z},\dot{\tilde{z}})} \end{bmatrix}, \quad (16)$$

where $\sigma(\tilde{x},\dot{\tilde{x}}) = \sqrt{\rho_x + \kappa_x(\tilde{x}^2 + \dot{\tilde{x}}^2)}$, $\sigma(\tilde{y},\dot{\tilde{y}}) = \sqrt{\rho_y + \kappa_y(\tilde{y}^2 + \dot{\tilde{y}}^2)}$, $\sigma(\tilde{\psi},\dot{\tilde{\psi}}) = \sqrt{\rho_\psi + \kappa_x(\tilde{\psi}^2 + \dot{\tilde{\psi}}^2)}$ and $\sigma(\tilde{z},\dot{\tilde{z}}) = \sqrt{\rho_z + \kappa_z(\tilde{z}^2 + \dot{\tilde{z}}^2)}$ are functions that define the instantaneous weight of each PVTOL controller in the composition of the final control signal. A detail is that such functions are similar to a positive nonzero gains (the small arbitrary values $\rho_x, \rho_y, \rho_\psi, and \rho_z$ guarantee that such functions are nonzero when the errors are all null).

Moreover, the calculation of the covariances related to the individual control signals obeys a logic of relevance. For instance, in the filter 1 the XZ-PVTOL controller calculates just the control signals $[u_\theta \;\; u_{\dot{z}}]$, so that the weight associated to such signals should be more meaningful. Therefore, the functions $\sigma(\tilde{x},\dot{\tilde{x}}), \sigma(\tilde{y},\dot{\tilde{y}}), \sigma(\tilde{\psi},\dot{\tilde{\psi}})$ and $\sigma(\tilde{z},\dot{\tilde{z}})$ generate positive values that influence in the estimation of the instantaneous value of the whole control signal and indicate the meaningfulness of the observed data. In this case, the closer to zero the covariance value is, the more relevant the correspondent observation (the individual PVTOL control signal) is. This is why for the filter 1, which effectively acts on $[u_\theta \;\; u_{\dot{z}}]$, the weight functions are $\sigma(\tilde{x},\dot{\tilde{x}})^{-1}$ and $\sigma(\tilde{z},\dot{\tilde{z}})^{-1}$, to give high weight for the control signal provided by the XZ-PVTOL controller when the x and z position errors and their variations are bigger, and $\sigma(\tilde{\psi},\dot{\tilde{\psi}})$ and $\sigma(\tilde{y},\dot{\tilde{y}})$, which correspond to the control signals $[u_\phi \;\; u_{\dot{\psi}}]$, associated to low weight values. Therefore, the weights associated to the individual control signals generated by each PVTOL controller are a function of how *observable* they are in the measurements. Control signals immediately visible in the measurements receive higher weights. Once the filter updates the estimate of the states using the new measurements, the covariance of the estimated states also changes, to reflect the information added, thus reducing the uncertainty. As a consequence, these filters fuse the control signals generated by the three controllers, resulting in a final control signal whose covariance is lower than the lower covariance associated to the three control signals inputted to the fusion engine. The output of the global filter, then, is

$$\hat{\mathbf{x}}_{fusion} = [\hat{u}_\theta \;\; \hat{u}_\phi \;\; \hat{u}_{\dot{\psi}} \;\; \hat{u}_{\dot{z}}]. \tag{17}$$

Finally, an important aspect of this approach is that to now no formal stability proof is available for the control system here proposed. However, a conjecture that such a system is effectively stable is established, based on the observation that there is no discontinuity in the control signal sent to the UAV, as it happens when one switches from one to other PVTOL controller (the control signal generated varies smoothly along the time of flight), and on the experimental results so far obtained using the proposed control architecture, some of them are discussed in the sequel.

IV. Experimental Results

Two experiments were run with the quadrotor *AR.Drone*®2.0, from Parrot, Inc., to compare the performance of the control strategies based on the switching between three PVTOL controllers and the fusion of the control signals generated by the same PVTOL controllers. Both experiments correspond to path-following tasks, the first one corresponding to a 3D 8-shaped path and the second one corresponding to a 3D ascending spiral.

The following two tables allow comparing the two control strategies. Table I summarizes the first experiment (8-shaped path), whereas Table II summarizes the second one (spiral path). Such tables show the flying time and the performance indexes ISE (integral of the squared error) and IAE (integral of the absolute value of the error), for the cases of switching between the PVTOL controllers and fusion of the control signals here proposed.

TABLE I

First experiment: following an 8-shaped path.

Strategy	Time $[s]$	ISE	IAE
Switching	448.0740	9.0940	80.9668
Fusion	124.6410	3.8203	21.5379

TABLE II

Second experiment: following an ascendent spiral path.

Strategy	Time $[s]$	ISE	IAE
Switching	690.95	44.2309	188.0470
Fusion	214.83	22.4165	61.2083

Besides such tables, Figures 5 and 6 show the graphics correspondent to the same experiments.

An analysis of the experimental results above described allow verifying that the strategy of fusing the control signals generated by the PVTOL controllers to design a controller able to guide the UAV in 3D navigation tasks has two quite interesting advantages. The first one is that the same task is accomplished in much less time, in comparison with the strategy of switching between the PVTOL controllers, what means that under such strategy the demand for energy to accomplish a certain task is much less. As for the second one, the positioning errors are much smaller, besides the fact that the path followed is much smoother. It is also remarkable that the lower time demanded to accomplish the task makes possible to use the proposed control architecture for accomplishing trajectory tracking tasks, what is not possible in the case of the switching strategy, as pointed out in [16].

V. Conclusion

In this work a control architecture is proposed to guide the 3D navigation of a quadrotor, based on the fusion of control signals generated by three controllers restricted to execute just PVTOL tasks. Although the objective of navigating in the 3D space using high level controllers suitable for 1D and 2D navigation has already been explored through the switching among such controllers, the solution based on the fusion of the individual control signals here proposed has shown to be much more effective, resulting in a faster and smoother navigation when regarding positioning and path-following tasks. An analytical way to assign the weight correspondent to each one of the three basic controllers is also proposed, which is a function of the errors related to the desired pose and thus is updated at each control cycle. As a result, a unique continuous control law is obtained, expressed as an analytical function, which allows giving higher weight to the basic controller more adapted to the task in each control cycle (although also considering the contribution of

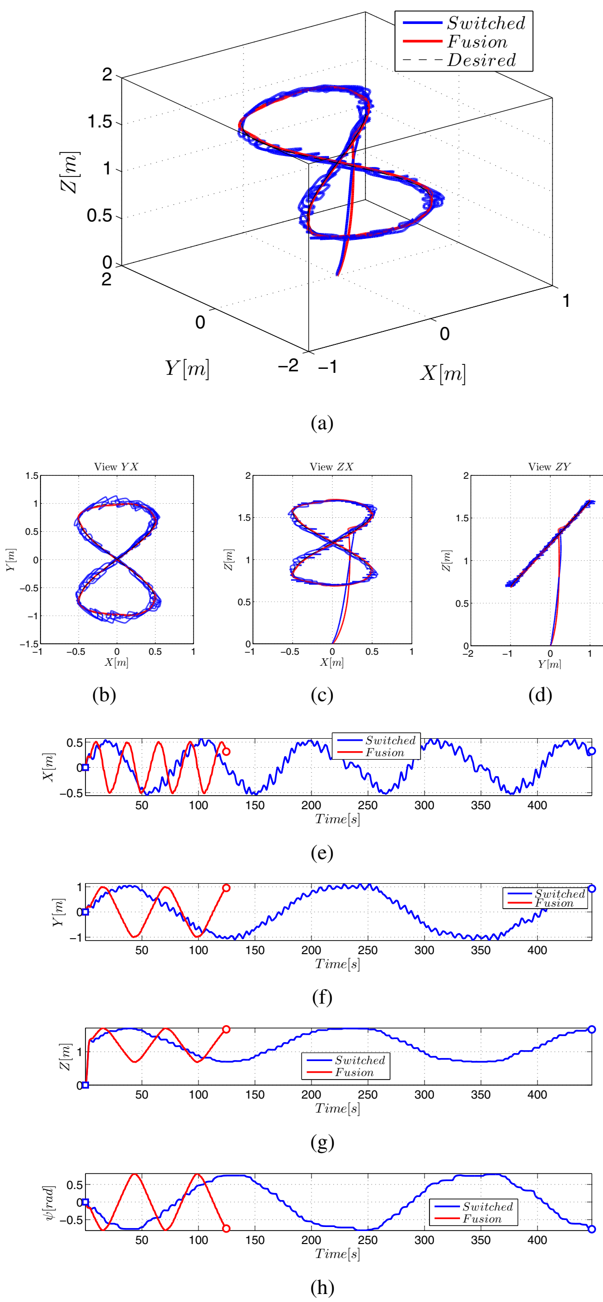


Fig. 5. Graphics correspondent to the first experiment.

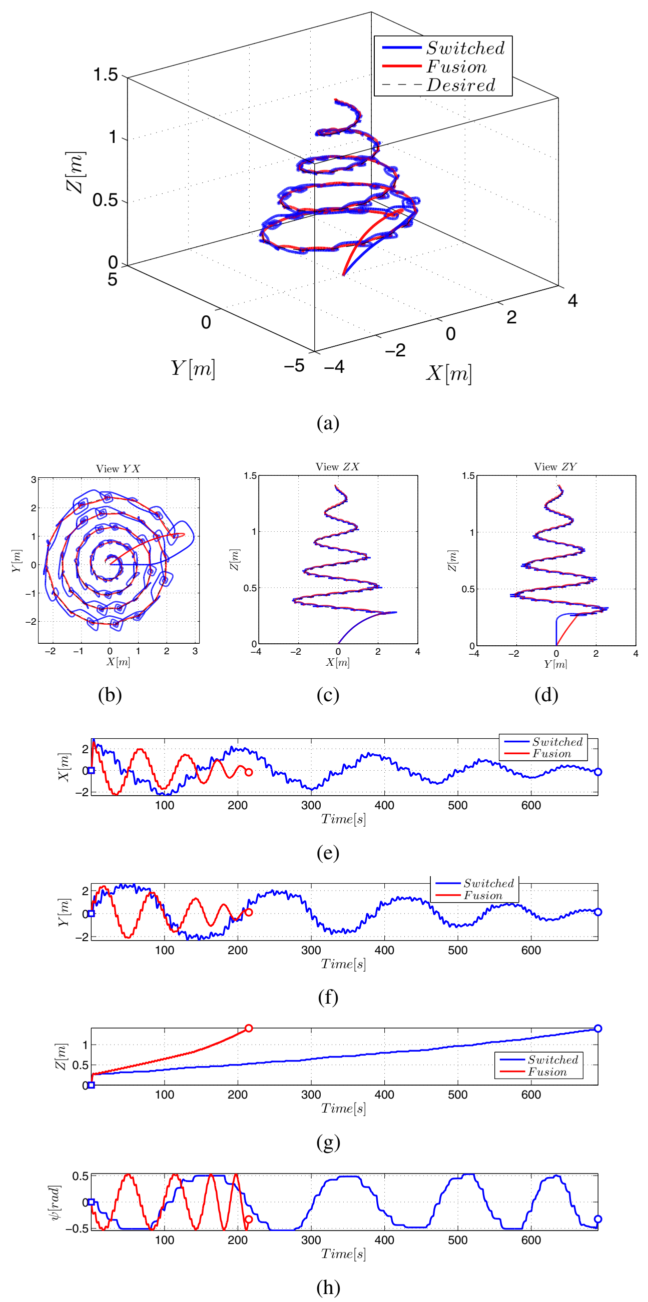


Fig. 6. Graphics correspondent to the second experiment.

the other two controllers). Moreover, it is also shown that the fusion of the distinct control signals, generated by controllers that have distinct control objectives, although sharing parts of the whole control objective, generates bounded control signals when adopting the weight functions here proposed. Finally, although the stability of the closed-loop control system based on the controller here proposed remains not proven, a conjecture is proposed, claiming that such a control system is effectively stable, based on the fact that the control signal does not suffer discontinuity and in the experimental results so far obtained, some of them presented in this work.

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