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FIXED-WING UAV ROBUST GUIDANCE STRATEGY BASED ON COMPOUND FLIGHT MISSION OF ON-GROUND TARGETS

José Lucas Gomes Olavo*, Leonardo Antônio Borges Torres, Tales Argolo Jesus*****
***Graduate Program in Electrical Engineering, UFMG, Brazil, **Department of Electronics Engineering, UFMG, Brazil, *** Department of Computing, CEFET, Brazil**

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Abstract

A controlled fixed wing unmanned aerial vehicle is modeled based on a simplified low dimensional nonlinear dynamical system with additive disturbances. The guidance strategy proposed on a previous work is extended for the accomplishment of more complex flight missions. The trajectory is composed by subsequent targets or the concatenation of arcs of circumferences that compose the goal mission. The strategy seems to be robust to additive perturbations representing norm bounded uncertainties on the execution of the compound mission by the UAV. Simulations are provided on area mapping and border patrol missions on the map of the city of Belo Horizonte.

1 Introduction

Small Unmanned Aerial Vehicles – UAVs have been increasingly used in different missions as a consequence of lower development costs associated with its on-board electronics and new airframe materials. Indeed, there are many manufacturers nowadays, specially in the realm of rotor-wing aircrafts [1, 2]. However, in missions where endurance is a very important performance indicator, fixed-wing UAVs can achieve a better trade-off between operational cost and mission accomplishment.

A drawback of using fixed-wing UAVs is the greater complexity in their guidance strategies due to the constraint of nonzero minimum velocity [3]. An excellent survey on different guidance techniques for a deterministic model of a fixed wing UAV can be found in [4].

In this paper we propose a guidance strategy that is a follow-up of our work on robust circulation of on-ground targets [5, 6], in which we consider constraints on the aircraft true airspeed and maximum turning ratio, together with inputs saturation and resilience to wind gusts.

Notoriously, the dynamic model plays an important role on the guidance and control strategy implemented [7]. The defined approach involves considering some uncertainties on a low order dynamical system that approximately represents the behavior of the controlled UAV [8, 9], in order to encompass the difference between the dynamical behavior predicted using this simplified model and the observed reality presented by the aircraft.

The robust guidance strategy was verified on flight missions composed of a series of singular circular trajectories that consider the specificities of the strategy already implemented and verified through simulations. Specifically, with the choice of subsequent targets or the concatenation of arcs of circumferences we can build a path for the UAV to robustly fly over long on-ground targets. The ultimate goal was evaluate the proposed guidance and control fixed-wing UAV method on a series of complex trajectories based on the basic on the fundamental concept proposed.

A key point in our approach is the assumption that a *controlled* UAV can follow a much simpler reference model that approximately represents its dynamical behavior in trying to fulfill its mission. We provide simulation results for the Aerosonde UAV [10], employing multi-loop low-level PID controllers (as commonly found in commercial autopilot hardware), to show the effectiveness of our strategy on area mapping and border patrol missions in the city of Belo Horizonte.

2 Robust Circulation of On-Ground Targets

We consider that a six degrees of freedom nonlinear UAV dynamical model [11] is satisfactorily controlled by low-level controllers carefully tuned [12]. The *controlled* UAV dynamics can be described by the following mathematical model (constant altitude) [3]:

$$\begin{aligned} \dot{x} &= v\cos(\theta), \\ \dot{y} &= v\sin(\theta), \\ \dot{\theta} &= \frac{1}{\tau_\theta}(-\theta+\theta_c)+\delta_\omega, \\ \dot{v} &= \frac{1}{\tau_v}(-v+v_c)+\delta_a, \end{aligned} \tag{1}$$

where x and y are the cartesian coordinates of the center of mass of the aerial robot, θ is the heading angle, v is the translational velocity, θ_c is the heading angle command, and v_c is the translational velocity command. The altitude dynamic behavior will not be explicitly considered for simplification purposes, since it is decoupled from the other states dynamics in our simplified reference model.

The terms δ_ω and δ_a are norm-bounded uncertainties, i.e.

$$|\delta_\omega| \leq \Delta_\omega, \tag{2}$$

$$|\delta_a| \leq \Delta_a, \tag{3}$$

where Δ_v, Δ_ω and Δ_a are positive real constants. These additive uncertainties are used to represent the effect of atmospheric disturbances that interfere on the fixed-wing UAV flight and to make the simplified model able to better represent the actual dynamical behavior of the controlled UAV, while respecting constraints related to the maximum limit for the turn rate, and the minimum and maximum limits for the translational velocity. The constraints considered are

$$|\dot{\theta}| = \frac{|\theta_c-\theta+\tau_\theta\delta_\omega|}{\tau_\theta} \leq \omega_M, \tag{4}$$

$$v_m \leq v \leq v_M, \tag{5}$$

where ω_M, v_m, and v_M are positive constants that represent, respectively, the maximum limit for the turn rate, and the minimum and maximum limits for the translational velocity.

Although we have relied on the simplified reference model (1), that is far from representing the dynamics of an uncontrolled aircraft. On [6] is demonstrated that this model represents satisfactorily the dynamics of the *controlled* UAV, in the sense of exhibiting small and bounded uncertainties δ_ω and δ_a when trying to accomplish a simple mission of UAV circulation on a fixed on-ground target.

The methodology to measure the existing discrepancies involves using the available information on the aircraft heading angle θ' and the aircraft translational velocity v' to compute the difference between the expected time-derivative values given by the simplified reference model without the additive disturbances and the actual time-derivative values obtained by means of simulation of the controlled nonlinear aircraft dynamical model with wind disturbances, such that

$$\delta_\omega = \dot{\theta}' - \frac{1}{\tau_\theta}(-\theta'+\theta_c), \tag{6}$$

$$\delta_a = \dot{v}' - \frac{1}{\tau_v}(-v'+v_c). \tag{7}$$

In the possession of the obtained values, it is possible to verify if the calculated values were superior at any time to the maximum norm-bounded uncertainties defined during the design of the guidance and control strategy.

In order to provide a direction to be followed by the UAV on a mission that converge and circulate indefinitely an on-ground circle in the counter-clockwise direction, without violating the constraints, it was proposed in [6] a robust guidance strategy based on a Finite State Machine (FSM), as illustrated on Figure 1. Succinctly, the stage Ω_s tries to make the UAV fly as close as possible to a straight line to quickly move away from the target circle, respecting certain conditions. On Ω_c the UAV robustly turns to the left without violating the constraints. Finally, in Ω_0 the controlled UAV follows the artificial vector field designed to provide a reference direction.

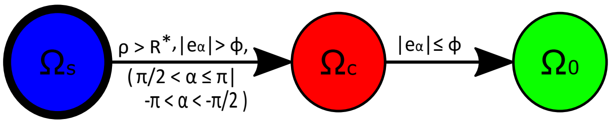

Fig. 1 Finite state machine of the robust guidance strategy.

It is important to be emphasized that Ω_s and Ω_c, differently from Ω_0, do not correspond to regions in the state space of the UAV. In fact, they are just operational modes of the controller of the robust guidance strategy that are sequentially activated in time according to the transition conditions presented in Figure 1.

The robust guidance strategy proposed is described by a constant translational velocity v_c, and:

$$\theta_c = \begin{cases} (\psi-\alpha) - \tau_\theta K_\theta \,\text{sat}\left(\frac{(\psi-\alpha)-\theta_0^{\Omega_s}}{\Gamma}\right), \text{(State } \Omega_s) \\ (\psi-\alpha) - \tau_\theta K_\theta \,\text{sat}\left(\frac{(\psi-\alpha)-\theta^{\Omega_c}(t)}{\Gamma}\right), \text{(State } \Omega_c) \\ \text{with } \theta^{\Omega_c}(t) = \theta_0^{\Omega_s} + \omega_\theta(t - t_0^{\Omega_c}) \\ (\psi-\alpha) - \tau_\theta \left[-v\frac{\text{sen}(\alpha)}{\rho} - K_\alpha \,\text{sat}\left(\frac{e_\alpha}{\Phi}\right) + \dot{\alpha}_r(\rho)\right] \\ \qquad\qquad\qquad\qquad \text{(State } \Omega_0) \end{cases} \tag{8}$$

where ρ and ψ are the radial and the angular coordinates of the aerial robot center of mass, respectively, $\alpha = \psi - \theta$, Φ and Γ delimit a regions named “Vector Field Cone” and “Vision Cone” in [6], $\text{sat}(x)$ is a saturation function and K_θ, ω_θ, K_α are adjustable parameters of the guidance law. Moreover, some inequalities must be respected while fulfilling the mission [6].

The proposed strategy aims to guide the aircraft to follow the control laws defined by the FSM on a progressive way, such that the UAV starting on a straight line movement will achieve a curve on the counter-clockwise direction, and finally try to follow the desired direction given by the artificial vector field [13]. However, the hybrid controller also needs to guarantee that the model uncertainties do not violate the maximum bounds even on the transitions between states of the guidance strategy proposed, as demonstrated on [6].

3 Flying Over Areas by Combining Circles

The guidance strategy originally proposed considered the achievement of flight missions that circulates only one fixed on-ground target. The mathematical tools and the control laws implemented were based on this specific geometric characterization of the mission. Therefore, if more complex missions are desired, it is necessary some improvements in order to guarantee a satisfactory dynamical behavior.

However, before increasing the complexity of the proposed strategy, one can imagine a more generalist flight mission composed of a series of individual missions that already consider the specificities of the strategy implemented and verified through simulations [6]. That approach would be a description of the navigation of a UAV on a higher level of abstraction, in other words, how to take advantage of the strategy implemented to fulfill more usual flight missions. Nevertheless, this extension involves respecting all constraints presented in the original conception of the problem, as well as the conditions of transitions between the states of the hybrid controller described on the FSM.

The goal is to verify the dynamic behavior of the aircraft during trajectories described by the implemented strategy. If the missions are accomplished successfully and the uncertainties of the simplified model remain limited, based on the norm bounded error modeling, the strategy extension can be conjectured for the description of more complex missions.

The design of different flight missions as remote area mapping, transmission lines tracking, verification of deforestation areas and border patrol are possible applicabilities for this generalist formulation of the problem. These descriptions are practical examples that could present a real functionality for the proposed control and navigation strategy.

3.1 Area Mapping

Area mapping missions are quite common within the unmanned aerial vehicle operating environment, as they can be considered a low cost alternative to aerial photogrammetry [14, 15]. Since the image pickup sensors have a high degree of definition, the UAVs are used for the design of surfaces using three-dimensional models.

In area mapping mission, the UAV flies through different target regions, over a period of time. This goal can be achieved by changing the center of the target circle at specific times during the mission, which promotes a change in the aircraft's movement towards the new defined target. The Figure 2 illustrates a compound mission with four distinct targets.

Using the original strategy, we have re-initialized the stage to Ω_s at specific time instants, with the requirement that the inputs and states constraints should be satisfied, and additive corrections terms δ_ω and δ_a cannot violate their pre-specified limits. In other words, the aircraft reaches a first defined target and after a time interval a new objective is proposed, so that the current position is equivalent to the initial condition of the next stage.

3.2 Border Patrol

A more complex mission is the border patrol of geographical boundaries. The boundary refers to a region that delimits a particular territory, segregating it from others. In applications involving surveillance, immigration control and territory demarcation, the use of UAV have a direct applicability on those scenarios [16].

In order to have guarantees that the constraints of the original problem will not be violated some adjustments were implemented. Two approaches were used: (*i*) to model the boundary via approximations of frontier regions by arcs of circumferences of different radius, and to make the aircraft flies through each arc during finite time intervals, changing the target circle at appropriate instants; and (*ii*) waiting for the aircraft to reach the final stage in (8) for a given circle and then changing the target to a new one without restarting the FSM. Other considerations, such as size and location of the circumferences, must be made to achieve the mission successfully.

The Figure 3 illustrates a region that uses this concept for border patrol application.

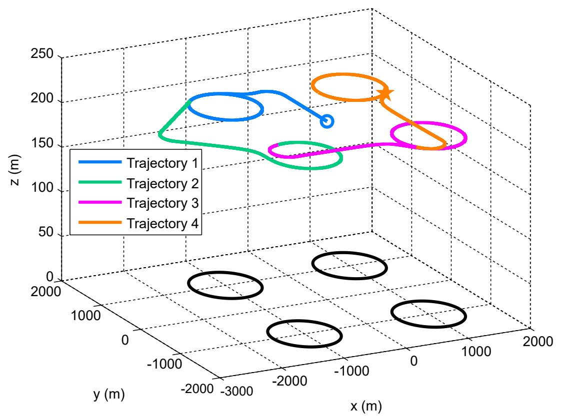

Fig. 2 Area mapping flight mission based on singular trajectories.

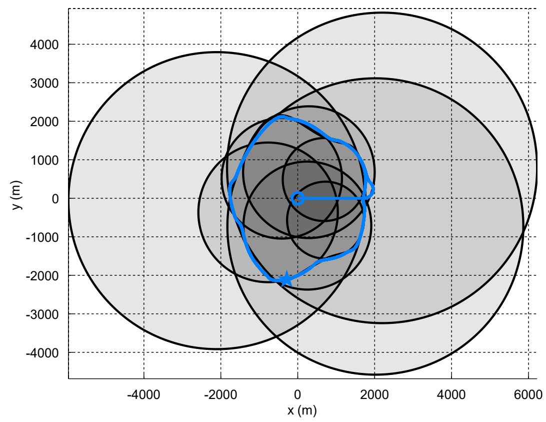

Fig. 3 Border patrol mission on the two-dimensional plane.

The first task involved approximating the borders of the region by arcs of circumferences. It was necessary to be cautious about choosing the necessary numbers of arcs to avoid abrupt changes during the flight mission. Given the location of the centers and the size of the circles that approach the boundary, the navigation mission directs the UAV to follow them, defining the intervals at which transitions may occur.

4 Numerical Results

In order to verify the applicability of the guidance strategy on compound flight missions, we developed simulations of both scenarios described above. The behaviors of the angular velocity and linear acceleration achieved by the controlled UAV and the simplified reference model were analyzed to verify if the difference between them are limited by the maximum values defined for the uncertainties δ_ω and δ_a in (1).

In case those uncertainties kept limited to the maximum values during the whole simulation, the extension of the proposed strategy, using some adjustments of the original goal of circulating a single on-ground target, did not contradict the results proven on [6].

4.1 Area Mapping

On the first scenario, it was analyzed the compound mission defined by the four distinct target circle illustrated on Figure 2.

The original controller proposed did not properly discriminate the FSM reset as verified on the area mapping application, where it moves from the state Ω_0 to Ω_s. However, this action is closely related with the natural activation of the guidance strategy on the FSM, because certainly there is some control, by means of a remote pilot, that precedes the proposed strategy.

Despite this particularity, the uncertainties for the angular velocity and the linear acceleration remain limited to the maximum values defined, as seen on Figures 4 and 5. The transition between targets make the aircraft to continue a movement tangent to the curve previously followed or to change the curvature of the movement to go to the new goal, so that there was no significant influence on the dynamic behavior presented.

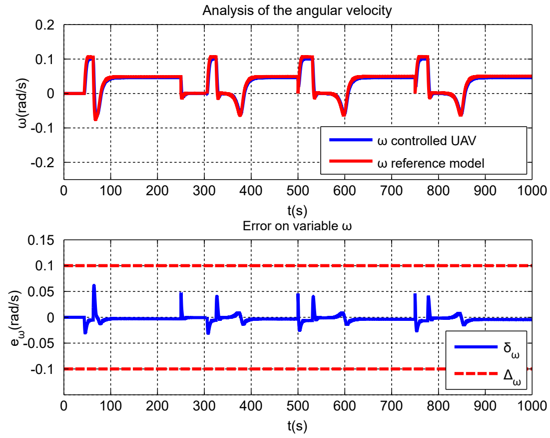

Fig. 4 Uncertainties on the angular velocity on the area mapping compound mission.

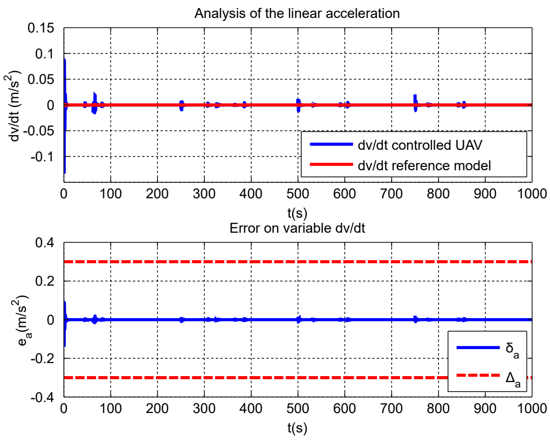

Fig. 5 Uncertainties on the linear acceleration on the area mapping compound mission.

In order to present a more tangible example of the compound flight mission, a simulation was designed on a real scale basis over a geographic region in the city of Belo Horizonte, in Brazil. In this simulation, a cartographic representation of the Pampulha region was used to define strategic points to which the UAV should be directed on a sequence mission.

The Figure 6 illustrates this area mapping, where the physical dimensions of sites and the

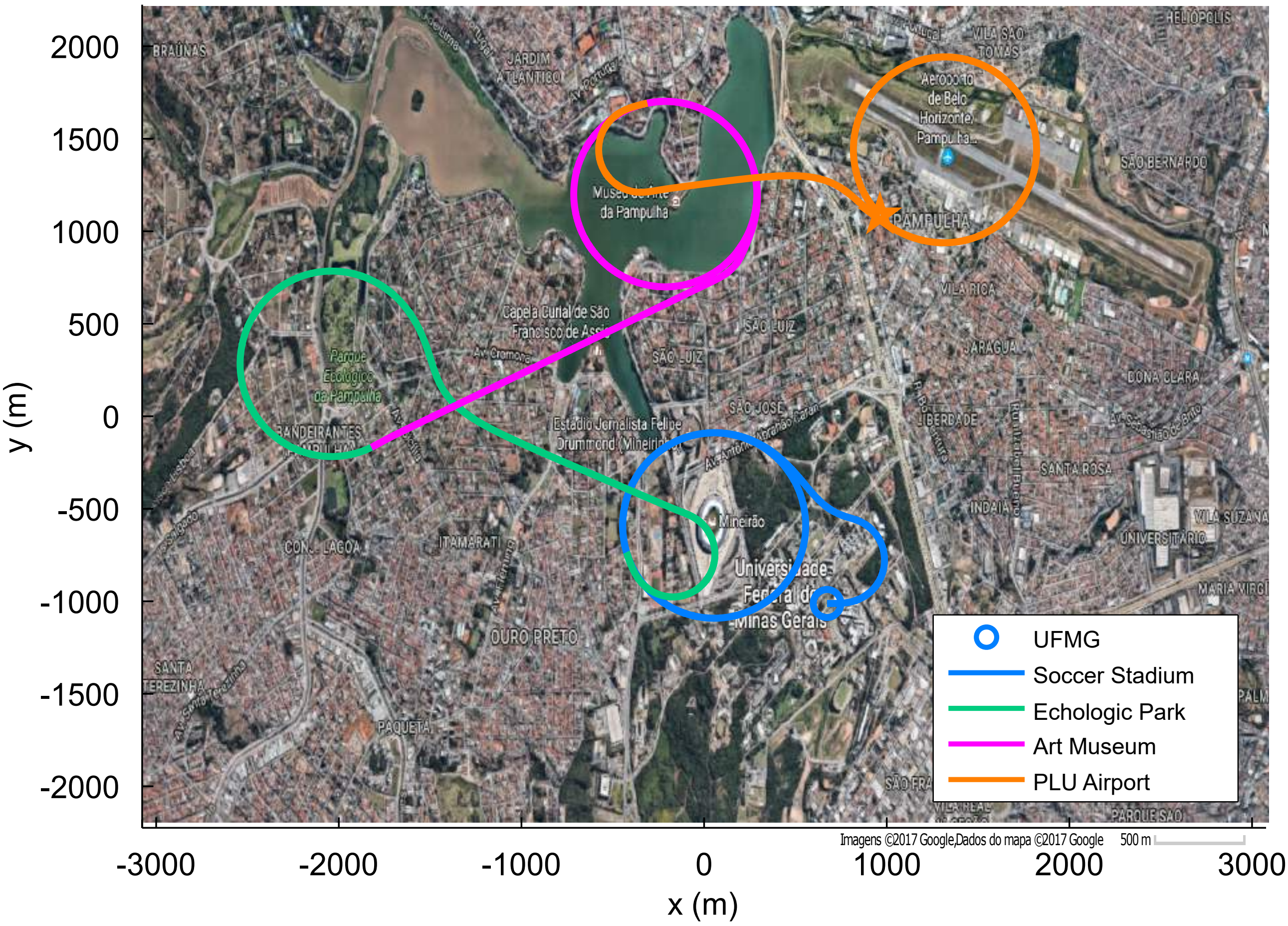

Fig. 6 Area mapping mission on the Pampulha region of Belo Horizonte.

500 m for the target circle radius were kept proportional to the map size. The dynamic behavior of the aircraft during the whole experiment have confirmed the robustness of the proposed strategy, in a way that no violations of the angular velocity and linear acceleration uncertainties occurred.

Certainly, in a real test the verified results would present adverse aspects to those considered in simulation. However, the simulation was developed to analyze the scalability of the mission and to demonstrate that, in fact, the area mapping may represent a branch of application of the proposed strategy.

4.2 Border Patrol

On the border patrol application, it was verified the dynamical behavior on the compound mission illustrated on Figure 3, in order to investigate if the controlled UAV added with norm-bounded uncertainties could follow the reference model properly.

The results demonstrate that the proposed strategy, together with the approximation technique through circumferential arcs and the adoption of constraints inherent to the specificity of the movement, is able to lead the aircraft to follow the border of the region satisfactorily.

The definition of intermediate areas between subsequent circumferences avoids abrupt transitions, thus providing satisfactory border tracing and success of the compound mission. Another important detail considered was that the circumferences must approximate the border following its inside curvature, so that the counterclockwise direction guarantees the correct trajectory.

As regards the uncertainties for the angular velocity and the linear acceleration of the aircraft, the Figures 7 and 8 illustrate that they remain limited during the simulation. The transitions between target circles of different radius did not result in violation of such values, so the extension of the proposed strategy for the border patrol did not invalidate the fundamental principles that characterize the original strategy.

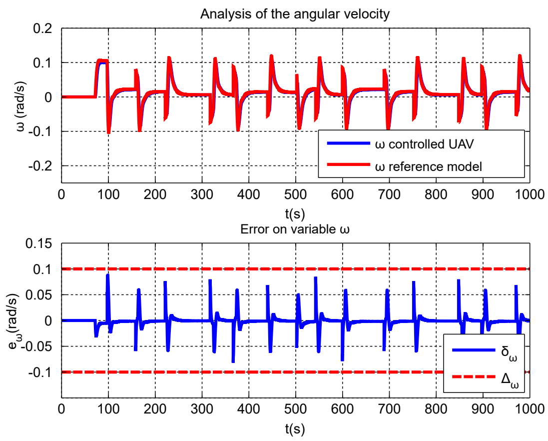

Fig. 7 Uncertainties on the angular velocity on the border patrol compound mission.

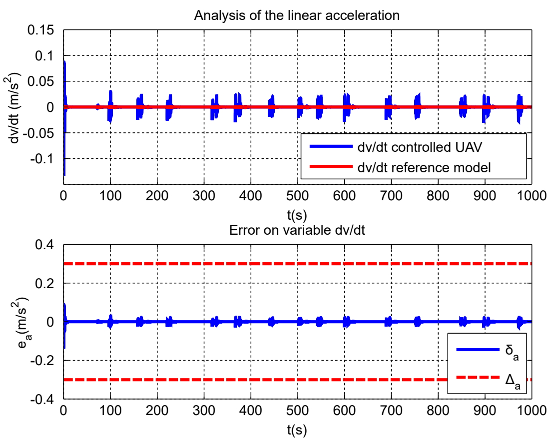

Fig. 8 Uncertainties on the linear acceleration on the border patrol compound mission.

On the same way, a simulation was designed on a real scale proportion to a physical space of the city of Belo Horizonte. The goal of the mission was to track the Contorno Avenue, using the technique portrayed. In order to fulfill this mission, the cartographic representation of the region was used to find the boundaries corresponding to the border that the UAV should circulate. Thus, the area was approximated via arcs of subsequent circumferences. The Figure 9 illustrates the trajectory performed by the aircraft, in simulation, for the border patrol. Similarly, the dynamic behavior of the aircraft during the whole experiment have confirmed the robustness of the proposed strategy.

As previously mentioned, this hypothetical example was used to endorse possible applicabilities that could be exploited with the extension of the proposed original strategy. The results show that with some refinements the strategy implemented can be used to describe a series of more complex missions, without violating the inequalities imposed on the simplified model and obtaining a satisfactory dynamic behavior of the aircraft.

5 Conclusion

An extension of the robust guidance strategy proposed on [6] was implemented aiming to accomplish of more complex flight missions than on-ground targets circulation. Simulated results show that the modified strategy can achieve a satisfactory dynamic behavior without violating the states constraints for a fixed-wing UAV, such as maximum turn-ratio, and minimum and maximum velocities, while being relatively robust to atmospheric disturbances such as moderate wind gusts.

It is important to mention that this work was a first attempt to extend the original guidance strategy to achieve more complex missions. Some refinements, specially on the mathematical proofs, are critically necessary to ensure the success of a variety of missions as area mapping and border patrol.

The main point to be considered in future research is the use of this robust analysis framework to other complex missions such as multi-agents coordination. It would also be interesting to verify this guidance strategy been applied on a real experiment on a fixed-wing UAV, that could capture realistic details imperceptible through simulations.

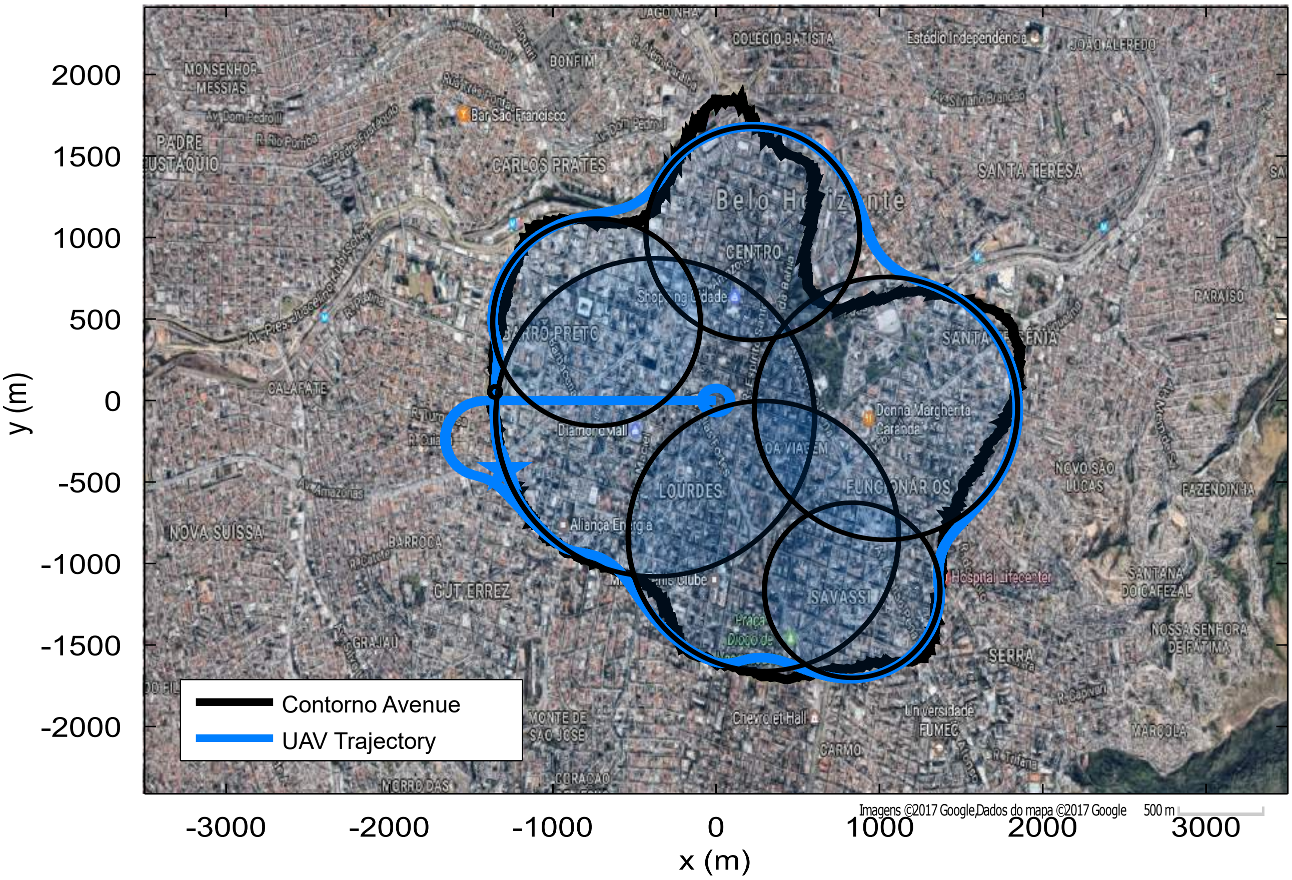

Fig. 9 Border patrol mission on the Contorno Avenue of Belo Horizonte.

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Contact Author Email Address

Please, do not hesitate to contact the authors in case of any questions or suggestions regarding this article. Contact information:

José Olavo: joselucas.olavo@gmail.com
Leonardo Torres: leotorres@ufmg.br
Tales Jesus: talesargolo@decom.cefetmg.br

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