Reviewer #1 (Other Reject):

The paper presents a theoretical model to perform collision avoidance by exploiting a quadrotor.

The authors reveal poor knowledge of avionics systems, since they consider a scenario where ADS-B is used as source of information. Anyway, ADS-B is a system that has been developed to support Separation Assurance rather than collision avoidance. Moreover, it can not be properly related to a quadrotor since a quadrotor flyies at altitudes where ADS-B is not reliable. The proper definition of Sense and Avoid requires an onboard sensor, such as a radar or a camera, to provide autonomous and reliable information about potential collision threats that are approaching the own aircraft.

We are developing a new approach for collaborative collision avoidance between unmanned and manned aircrafts. Due the drone limitation of payload weight/power, and the ADS-B miniaturization, the simulation results show that it is viable to use ADS-B to detect and avoid collisions autonomously. See discussion in Section I on Page 2: “In general, sense-and-avoid (SAA) technology could be divided into two categories, namely collaborative and non-collaborative. …”

Considering the scenario reported and the very limited timeframe, i.e. less than 10 s, used for the example the reported validation simulation is not feasible on typical Sense and Avoid scenarios.

It is feasible with collaborative SAA. See Section Section I on Page 2.

The proposed method accounts for the knowledge of distance to assess the start of a collision avoidance maneuver. Indeed, the typical Sense and Avoid systems developed for quadrotors are based on visible cameras that are lighter than radars or laser scanner. As a consequence, no distance information could be available.

Distance info is available from collaborative SAA. See Section Section I on Page 2. For this specific reason we are using ADS-B for collaborative collision avoidance.

Finally, the presented numerical simulation does not account for any disturbance such as typical sensor errors, wind and turbulence and so on. In this case, flight test are mandatory. In particular, flight test involving quad rotors could be developed at low-cost.

The readability of figures 5 and 6 shall be improved. Moreover, the abbreviation of "seconds" is "s" and not "sec" that can be confused with "secant".

Sensor noise and wind disturbance are added in the hybrid control scenario. See Section V-B.

Flight test is not possible at the current stage due to limited hardware resource. See Section V. “The simulation is expected to be realistic, although a hardware implementation is necessary to confirm the effectiveness of the hybrid controller. However, the hardware implementation is too involved, and thus not presented at this stage. It will be left as future work.”

Figure 5 is enlarged, and should be visible and legible. Figure 6 is re-formatted.

Abbreviation of “seconds” are all revised to “s”.

Reviewer #1 (Remarks to the Author - Include in AESS Magazine?):

Yes, after resubmission.

Reviewer #1 (Remarks to the Author - Does the introduction state the purpose of the submission?):

The introduction is more related to generic "Sense and Avoid" rather than to the specific scenario handled by the authors. More specific indications about the type of application related to "type G" airspace and quadrotors should have been included.

The new introduction explicitly addressed class G airspace, and identified the aircraft of interest to be helicopters and quadrotors flying at low altitude. See Section I on Page 1 and 2. “To formulate the collision avoidance problem, we first identify the manned and unmanned aircraft of interest …”

Reviewer #1 (Remarks to the Author - Is the paper clearly written and well organized?):

Yes. Some figures should be more readable.

Already addressed above.

Reviewer #1 (Remarks to the Author - Briefly, describe the contribution of the submission.):

A multi-mode control system for quadrotors is presented. In addition to a sliding mode position controller developed for standard cruise a specific safety mode has been developed for collision avoidance. Result produced by an intial stage simulation are presented.

Reviewer #1 (Remarks to the Author - General suggestions for improving the submission (if any).):

Provide specific issues about free flight of quadrotors in the introduction. Consider alternate information source as ADS-B. What is the impact on the developed control strategy if visual cameras are used that do not provide distance information?

Section I Paragraph 1: “If thousands of drones were flying freely in urban areas without any safety control, they would become a huge danger to existing aircraft.”

Alternative info sources are discussed in collaborative SAA. See Section Section I on Page 2.

There is no visual cameras capable of performing reliable collision avoidance. That is why we need collaborative SAA. See Section I on Page 2. “The collision avoidance problem of interest involves high-speed vehicles. Typical quadrotors and helicopters can travel at 30m/s and 70m/s, respectively [?, ?]. In the worst-case head-on collision, assuming an avoidance reaction takes 5s, then a range requirement of 500m is implied. This result completely excludes the possibility of non-collaborative SAA.”

Reviewer #2 (Remarks to the Author - Include in AESS Magazine?):

The manuscript in its present form cannot be accepted for the inclusion into AESS magazine due to the excessive mathematical detail. The authors shall revise the manuscript to make it understandable by a wide engineering based audience.

I tried my best to reduce the mathematical detail. However, it is impossible to talk about collision avoidance and navigation without math at all.

Reviewer #2 (Remarks to the Author - Does the introduction state the purpose of the submission?):

Yes

Reviewer #2 (Remarks to the Author - Is the paper clearly written and well organized?):

yes

Reviewer #2 (Remarks to the Author - Briefly, describe the contribution of the submission.):

The manuscript describes a hybrid controller that relies on ADS-B to perform optimal collision avoidance maneuvers with a quadrotor. Specifically, the position controller and the avoidance controller are formulated separately and then combined according to a transition logic aimed at optimizing the overall maneuver

Reviewer #2 (Remarks to the Author - General suggestions for improving the submission (if any).):

I have the following suggestions to improve manuscript clearness and quality:

- Introduction, pag.2, the authors shall provide at least a reference supporting the statement concerning the lack of alternative collision avoidance technologies capable of replacing ADS-B

I updated the references on both non-collaborative and collaborative SAA. The limitation on non-collaborative SAA is sensor range. Alternative collaborative SAA is DSRC. See Section I on Page 2. “In general, sense-and-avoid (SAA) technology could be divided into two categories, namely collaborative and non-collaborative. …”. (I didn’t see anywhere in the paper the range of non-collaborative technologies)

The range of non-collaborative technologies is mentioned in the following paragraph:



Reference 5 is a 360 deg. Radar with 100m range; reference 6 is a Hokoyo UTM-30LX Lidar with 30m range (or 60m max with additional accessories).



- Literature review-position controller: the authors say that to develop the sliding mode controllers the approach of ref. 13 is followed. They speak of a simple application of the approach described in ref. 13. Thus, from the manuscript it is not possible to understand what is the original contribution (if any) of the authors in the development of the position controller

The original contribution is on horizontal position control. The original reference 13 only provide controller formulation on roll, pitch, yaw, and altitude control. Traditional horizontal position control has a term explosion issue. See Section II-A for the contribution. “In this paper, we resolve the term explosion problem by combining nonlinear control methods with dynamic surface control (DSC) techniques. Specifically, we augment the quadrotor model with two first-order filters from the DSC literature [?]. With the DSC filters, we were able to access slightly lagged versions of the required time derivatives, and indirectly formulate concise control laws, to fully control a quadrotor, including horizontal positions.”

- literature review-avoidance controller: the same as above. The authors say that in practice they apply the approach of ref.19. Thus, again, what is their original contribution in terms of avoidance controller?

The approach in ref 19 only accounts for simplistic 2D dynamics. I only used it as an initial guess, and iteratively enlarge the safety set, so that it also works under 3D dynamics. See Section II-B. “In this paper, we modified the safety controller in [?] to fit our drone-helicopter scenario. First, we only use the safety set from [?] as an initial guess, and enlarge the safety set via an iterative algorithm to account for 3D dynamics. Second, the optimal control is only applied to the quadrotor, and the helicopter flies freely as if the quadrotor does not exist.”

- Dynamic model: please provide at least a reference for the model in Eq.(1)

Reference provided. See Section III-A. “First, we need a quadrotor dynamic model. We adopt the same model introduced in [?], with a different notation.”

- Position controller-subsection A: the subscript d represents desired values of the variables, i.e. values to be tracked so to null the tracking error. Instead, variables without the d subscript represent actual values of the variables. If this definition is used, theta and phi should represent actual pitch and roll values, not pitch and roll required to track X and Y. In my opinion it is necessary to better clarify this point.

I re-wrote this section to clarify the confusion. See Section III-B.

- Safety controller - subsection A: it is not clear how axes x12 and y12 are defined. Please specify. It seems that all the parabolas within the avoidance set should terminate on the safety set so that they are tangent to it. However, from figure 2.b it seems that the parabolas intersect the safety set. Is the superscript \* used for the control input u1 indicating optimum value? Please specify. How densely we need to sample the optimum angle, theta1, to effectively generate the avoidance set?

I re-wrote this section to clarify the confusion. See Section IV.

Axis definition: “Note that the relative frame is rotated such that $\dot{x} (t\_0)=0$ and $\dot{y}(t\_0)<0$ on $\partial K\_h$. Therefore, points on $\partial K\_h$ has purely downward velocities.”

Figure 3 is re-drawn. Now, the red parabolas should look tangential to the circle.

“\*” does indicate optimum. “Follow the derivation in \cite{hoffmann2008decentralized}, we obtain the optimal acceleration for $t \in [t\_0,0]$ in [?]).”

The density of the optimal angle sampling is specified in Section V-A. “All safety sets are produced by griding $120$ points evenly for $\theta\_h^\*\in[0,\theta\_c] \cup [\pi-\theta\_c,\pi]$”

- Simulation: quadrotor parameters shall be included in a table. It is not clear if these parameters refer to a real quadcopter? Please include a reference. It seems that showed simulation results do not consider neither perturbations (wind?)or uncertainties. It is stated that this is not essential in this paper. My opinion is the opposite: behavior in presence of perturbations and robustness to uncertainties is crucial to assess the validity of a control approach, especially in this case in which the approach combines two controllers and the combination performance and/or the transition logic can be seriously affected by uncertainties.

How do you select the adopted values of key parameters of the sliding mode controllers? In addition, they shall be included in a table.

Parameters in the current form looks more clear than in a table.

The parameters are chosen to represent a realistice 3DR solo quadrotor. A reference is given. Please refer to Section V to see the justification on some key parameters. “In this paper, we use the parameters in equation (?) to mimic a realistic model (3DR Solo [?]). We could not guarantee the parameters to cover all possible quadrotors, but we do choose conservative parameter values carefully. There are three uncertain key parameters which dominates the simulation results, namely the rotational inertia (RI) $I$, the translation drag coefficient $c\_t$, and the communication delay $\Delta t\_{delay}$.”a

Wind disturbance and sensor noise are added in the hybrid controller simulation. See Section V-B.

The parameters of the sliding mode controllers are not critical in the simulation. Please do not give too much attention on it. A large range of parameters are possible. There is no general method on choosing the parameters other than trial and error. I removed that section to clear the confusion.

In describing the safety controller behavior (Fig.5) it is stated that the desired pitch exhibits some variations at the beginning and the end of the avoidance maneuver. The authors shall explain why.

I added the explanation. See Section V-A(1). “The avoidance duration is shortened to half as much ($2.6 s$) when $a\_{max}=10m/s^2$, but the desired pitch $\theta\_d$ has some variation at the beginning and the end of the avoidance. The variation exists because the quadrotor could not achieve the desired acceleration instantaneously due to rotational inertia (RI).”

Fig.7 shall be included in the sub-section C. The smaller plot inside the large one cannot be clearly visualized. Use sub-plots or eliminate. In addition, continuous black line almost completely covers dashed blu line. Please, specify this in the text.

I chose to eliminate the small subplot in Figure 8. The lines are now clarified in Figure 8(b) and explained in the text. See Section V-B. “Figure ? shows the time history of the horizontal command and control signals. In all subplots, the black solid lines give the actual signal trajectory. In the $X$, $Y$, and $Z$ time history plots, the red dashed lines indicate desired destination. In the $\theta$ and $\phi$ plots, the blue dashed lines show the command generated from the angle controller, and the red dashed lines give command from the position controller.”