

Evaluation of separation strategies for Unmanned Aerial Systems

M. Pérez-Batlle, E. Pastor and X. Prats
Technical University of Catalonia
Castelldefels, Spain
Email: [mpbatlle]@ac.upc.edu

Abstract—This paper analyzes loss of separation scenarios when an Unmanned Aircraft (UA) enters in conflict with a much faster airplane flying at the same altitude. Separation distances are analyzed in terms of minimum heading changes and reaction times. Results show that maneuvers need to be performed well in advance if the (low-speed) UA is the aircraft that changes its heading. In some cases the time in which the UA and the intruder are in conflict could be too long, and may even involve multiple airliners flying over the same airway. Given that standard separation strategies may have a negative impact on the UA mission, in this paper a set of pre-planned separation maneuvers are proposed. These maneuvers aim to improve the situational awareness of both air traffic controller and UA pilot-in-command, but also to disrupt as less as possible the mission performed by the UA and to minimize the uncertainty in the reactions the UA may adopt autonomously if the link with the ground station is lost. Some preliminary real-time simulations are shown, using a UA ground station simulator linked to a air traffic control simulator.

I. INTRODUCTION

In civil aviation, several layered mechanisms are present to minimize the probability of collision with other aircraft. Generally speaking, they are categorized into two main functionalities: separation assurance and collision avoidance. Separation assurance aims at keeping minimum distances between the aircraft and potential intruders. A loss of separation is considered a serious issue and ideally, it should never occur. Nevertheless, a collision avoidance functionality can prevent an imminent collision in case of a loss of separation as a last resort maneuver. In manned aviation, some Airborne Collision Avoidance Systems (ACAS) are already implemented and installed in civil aircraft, such as the TCAS (Traffic Collision Avoidance System). Moreover, regarding today's developed Air Traffic Control (ATC) systems, the Short Term Conflict Alert (STCA) system can also alert the Air Traffic Control operator (ATCo) of short term potentially conflicting flight paths. The STCA is not intended to be a separation assurance tool and like its airborne counterpart (the ACAS), it is used as an additional *safety net* [1].

Several other collision avoidance models, ranging from abstract concepts to prototype systems being evaluated or used in laboratories, have also been proposed aiming at increasing levels of automation in air traffic conflict detection and resolution (see [2] for a review on this topic). These algorithms typically compute the future position of the aircraft based on projections of the current aircraft states into the future. The

performance of these algorithms is rapidly degraded if the time horizon of the prediction increases, due to the inherent uncertainties in aircraft flight paths. Nevertheless, since collision avoidance is considered as a last resort maneuver, these detection times can be sufficiently small to still achieve good results in the predictions. Obviously, the same methodology cannot be applied for separation assurance purposes.

Nowadays, separation in controlled airspace is typically responsibility of the ATC, which issue clearances to the aircraft in order to maintain minimum separation values. Some systems, however, have already been proposed to increase the automation levels of these manual separation assurance processes. For example, as an ATCo support tool, the Medium Term Collision Detection (MTCD) system computes initially the trajectory of the aircraft from the flight plan using performance parameters and meteorological information and then, refines it by monitoring the actual performance of the aircraft [3]. Similar concepts are brought at cockpit level with the Airborne Separation Assurance Systems (ASAS), which aim to delegate separation tasks from controllers to pilots [4]. Furthermore, SESAR and NextGen programs propose new paradigms that rely on accurate design and execution of four-dimensional trajectories that are expected to transition from radar control to trajectory-based operations. The accuracy of these 4D systems, however, must rely on aircraft intent information. Otherwise future flight paths can not be deduced with certainty from only past flight path information, current state vectors or by extrapolating (even with error free) the information of those state vectors [5].

During the last decade, the interest of using Unmanned Aerial Systems (UAS) for civil missions and applications has increased significantly [6], [7]. Yet, the lack of a regulation basis concerning their certification, airworthiness and operations is still banning them into non-segregated airspace [8]. Among all UAS possible applications, surveillance missions will be perhaps the most numerous [9]. In these missions, UAS will not operate as current commercial aircraft, that fly *point-to-point missions*. They will possibly loiter over certain areas performing all kinds of *non-conventional* flight plans (such as scans, perimeter loops, etc.) that will change dynamically during the flight, according to the mission needs. Moreover, most of the Unmanned Aircraft (UA) will have poorer flight performance than commercial airliners (in terms of cruise speed and climb/descent performance, for instance), but will

likely operate at very similar altitudes. Finally, the a loss of data-link situation with the UA must also be considered and, depending on several parameters (such as the UAS particularities, the type of airspace, the distribution of populated areas below the flight path, etc.), this data-link lost contingency will be handled in a way or another.

For all these reasons, the conflict detection and resolution functionality can become an issue in a real UAS implementation. While extensive research has been devoted to collision avoidance algorithms that take into account the particularities of UAS, most of them inheriting from robotics and control theory applications [10]–[16]; few researchers have addressed the separation problem for UAS. Some proposals indeed, implement separation minima in their algorithms (like for instance [11]), but they are in general focused in very small UA and typical separation values are in the order of meters. Yet, if bigger UA are expected to fly into non-segregated airspace, larger separation values (such as 5 NM) will have to be considered [17].

This paper focuses on separation maneuvers for UAS and analyzes a simple case where a UAS enters in conflict with a much faster airplane flying at the same altitude. Different requirements are analyzed in terms of heading changes and minimum reaction times in order to maintain separation between both aircraft, assuming that the intentions of both are known. Since today’s standard separation strategies may have a negative impact on the mission, implying a deviation from the desired surveillance track, in this paper we propose pre-planned separation maneuvers. They aim to improve the situational awareness of both ATCo and UAS pilot-in-command, but also to disrupt as less as possible the sequence of the mission performed by the UAS and to minimize the uncertainty in the reactions the UA may adopt autonomously, in case the link with the ground station is lost.

II. CONFLICT GEOMETRY EVALUATION

Separation between manned aircraft has been achieved in controlled airspace by ATCo¹, with strict flight plan adherence rules and continuous monitoring of conservative safety volumes around each aircraft. In this way, potential violations of these volumes can be detected and ATCo can request aircraft trajectory adjustments, usually issued by voice commands. This manual process may take from tens of seconds to minutes depending on the performance of the communications, surveillance and navigation equipments, the workload of the ATCo and the aircraft crew, etc. Given all these parameters, minimum separation distances can be determined.

Controllers know beforehand the flight plan of the aircraft and/or ask the aircraft crew for position reports. With this information, they can figure out the different aircraft future positions. Vertical separation between two aircraft is typically 1000 ft (or 2000 ft above a certain altitude). If no radar is available, procedural control is applied and horizontal separation values can range up to 80 NM in some situations. On the

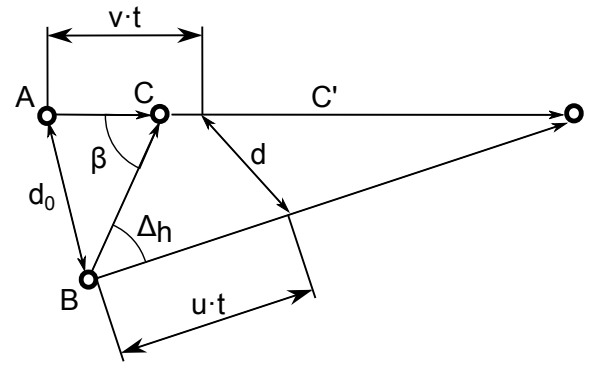


Fig. 1. Conflict geometry.

other hand, if radar control is possible the minimum separation horizontal distance can be reduced to 5.0 NM, or even 3.0 NM when radar capabilities at a given terminal area so permit [17].

One of the most important factors when detecting and solving a separation conflict, is the relative flight performance between the conflicting aircraft. With the possible introduction of UAS into civil non-segregated airspace, separation conflicts between UA and conventional airliners may occur. Such conflict geometries need to take into account the notable differences in flight performance between the UA and such an intruder. It might happen that changing the UA flight level, in order to maintain separation, would not be a possible solution due to the poor climbing or descending performance of the UA at cruise altitudes. Similarly, changing the UA heading will have to be executed well in advance if the UA is flying at a speed significantly slower than the intruder.

This section evaluates a number of simple conflict scenarios between a typical MALE UA (a GA MQ-9 Reaper²) and a jet airliner intruder, assuming that both aircraft will remain at the same altitude and that separation will be guaranteed by changing the heading of one of the aircraft. Minimum separation values of 3.0 NM and 5.0 NM are retained in the following simulations. Furthermore, since UAS operations might be subject to higher separation minima (to consider, for instance, latency issues, lost-of-link emergencies, etc.), we have also considered a hypothetical separation of 10 NM as illustrative example of an increased radar separation value.

A. Conflict and aircraft performance models

Figure 1 summarizes the conflict geometry studied in this paper. One aircraft (typically the airliner) is located in point A. We assume that it is flying at a constant speed (v) and altitude. At the same time, the second aircraft (typically the UA) is placed at point B. We will also consider that it is flying at a constant speed (u) and the same altitude than the other one. Both aircraft are moving towards the same position (point C). Points A and B are placed in such a way that both aircraft will arrive to C at the same time. In order to avoid this conflict we assume that the ATCo commands aircraft placed in B to change its heading (Δh). We want to know which is the

¹In non-controlled airspace, separation is assured by applying *see and avoid* rules [18].

²General Atomics Reaper performances are obtained from <http://www.globalsecurity.org/intell/systems/predatorb.htm>

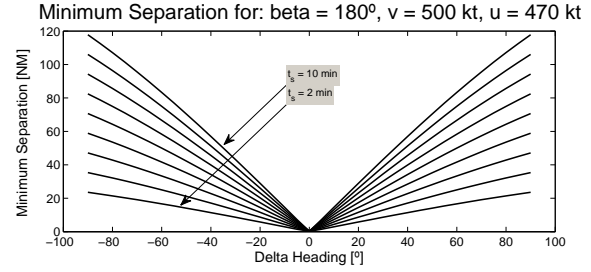
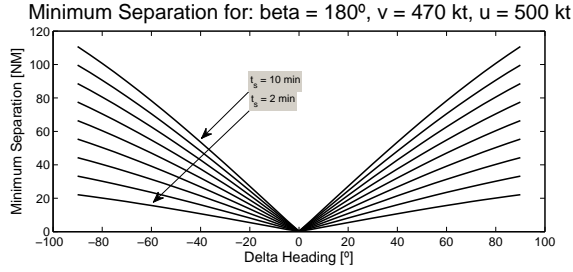


Fig. 2. Forward conflict in which (a) the slowest aircraft performs a separation heading change and, (b) the fastest aircraft performs the heading change.

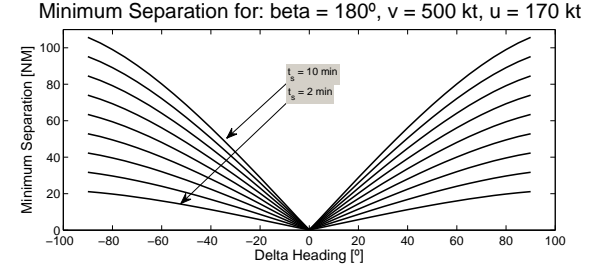
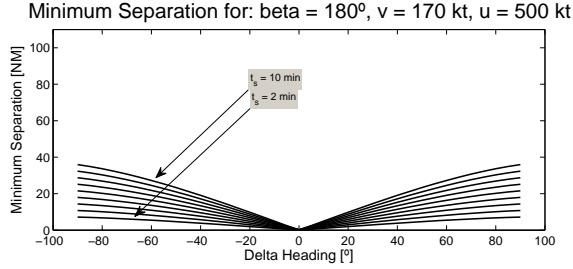


Fig. 3. Forward conflict in which (a) the UAS performs a separation heading change and, (b) the intruder performs the heading change.

minimum absolute distance between both aircraft d_{sep} , along their flight paths, as a function of Δh . We still have a degree of freedom to place points A and B : the Time to Conflict (t_c). This time is defined as the amount of time elapsed between the instant the aircraft changes its heading, in order to start the separation maneuver, and the time that both aircraft would have meet if no heading changes were applied (i.e. the time when both aircraft reach point C).

Regarding to the performance model, only the speed of each aircraft (at the considered altitude) has been taken into account. Table I summarizes them.

Aircraft Model	Speed
Airbus A320	$u = 500kt$
Boeing B737	$w = 470kt$
General Atomics Predator-B	$v = 170kt$

TABLE I
AIRCRAFT MODELS AND SPEEDS CONSIDERED

Another aspect that has to be taken into account is which plane is going to execute the heading correction in order to maintain separation. According to the conflict geometry, if we want to maximize the minimum absolute distance between the aircraft, we have to minimize their relative speed. When the aircraft speeds are similar, it makes no difference which aircraft performs the separation maneuver. Conversely, when the speeds are not similar, ATCo will achieve better results for the same Δh , if the fastest aircraft deviated from its flight path rather than the slowest one. Yet, it is worth assuming that in the future manned commercial aircraft might have higher priority than the UAS when facing conflicting trajectories. Thus, in this paper, we analyze both cases and either the UA or the

intruder can change its heading to avoid the conflict.

B. Forward separation conflicts

We define a forward conflict as a particular case of the conflict model, when $\beta = 180^\circ$. In this case, each aircraft will move towards each other with the maximum possible relative speed for the v and u considered before.

An example of this scenario is shown in Figures 2 and 3. In Figure 2, the conflicting aircraft are the Airbus A320 and the Boeing 737, which have similar cruise speeds. On the other hand, in Figure 3, the Boeing 737 has been replaced with the General Atomics MQ-9 Reaper UA, with a much lower cruise speed. For both Figures, β is fixed to 180° and the plot on the left exposes the simulation results when the slowest aircraft performs the separation heading change. Conversely, the plot on the right exposes the same situation but now, is the fastest aircraft who performs the separation maneuver. In the x-axis Δh has been plotted while, in the y-axis, the minimum absolute distance between aircraft is depicted. Each line represents a different Time to Conflict t_c , which is discretized in steps of 1 minute, from 2 to 10 minutes.

As expected, the lower t_c , the lower minimum separation distance achieved for a given Δh . As exposed before, while plots of Figure 2 are similar, the ones of Figure 3 differ significantly. Therefore, in the last case, there are clear differences in the results depending on who performs the separation assurance maneuver when aircraft speeds are dissimilar. For example, in Figure 3, if aircraft are situated at $t_c = 5$ minutes from the conflict point and the reaction maneuver is defined by $\Delta h = 20^\circ$, the minimum achieved separation distance is 14 NM or 5 NM depending on who performs the maneuver. Therefore, there is a relative difference on separation factor of

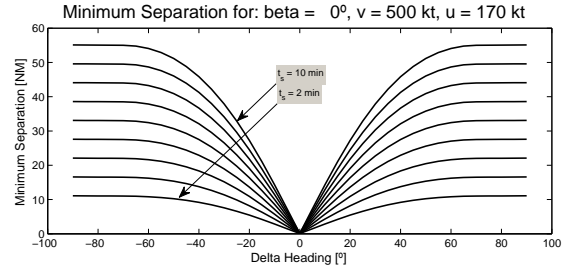
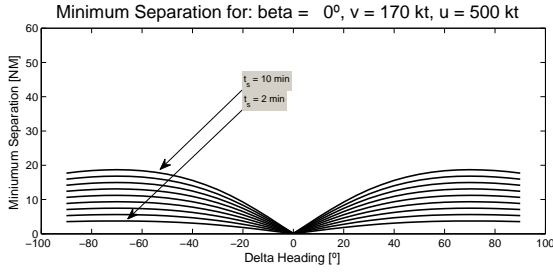


Fig. 4. Backward conflict in which (a) the UAS performs a separation heading change and, (b) the intruder performs the heading change.

2.8 for this particular case. However, in Figure 2, the minimum achieved separation distance is 14.47 NM or 13.6 NM with a factor of only 1.06.

Table II summarizes the minimum Δh needed to ensure lateral separation minima for several Times to Conflict (t_c). Δh values range from 5° to 90° in steps of 5° . If we compare both tables, the differences in the results depending on who performs the separation assurance maneuver become clearer. For instance, if a lateral separation of 5 NM is needed to be ensured and the conflict has been detected 5 minutes in advance, a minimum heading change of 25° is necessary if the ATCo commanded the UAS to perform the separation maneuver. Conversely, only a minimum heading change of 10° is necessary if ATCo commands the airliner.

Separation Minima	Δh for the UAS t_c [minutes]			Δh for the intruder t_c [minutes]		
	2	5	10	2	5	10
3 NM	35°	15°	10°	15°	5°	5°
5 NM	55°	25°	15°	20°	10°	5°
10 NM	N/A	45°	25°	40°	15°	10°

TABLE II
MINIMUM Δh TO ENSURE LATERAL SEPARATION ($\beta = 180^\circ$)

C. Backward separation conflicts

We define a backward conflict as a particular case of the conflict model, when $\beta = 0^\circ$. In contrast to the previous case, both aircraft have the same heading. The fastest aircraft will move towards the slowest one, chasing it, with the minimum possible relative speed. Figure 4 and Table III show the simulation results for this case. As before, there is a clear difference of results depending on which aircraft performs the heading change. Nevertheless, the differences are less important. For instance, if a lateral separation of 10 NM is needed, and the conflict has been detected 10 minutes in advance, a minimum heading change of 25° is necessary if the ATCo commanded the UAS to perform the separation maneuver. Conversely, only a minimum heading change of 10° is necessary if the ATCo commands the airliner.

Unlike forward conflicts, some conflict geometries become unsolvable if ATCo commands the UA to perform the separation maneuver. That means that the minimum separation distance between both aircraft cannot be achieved. For instance, if

$t_c = 2$ minutes (the typical STCA look ahead time) and if the separation maneuver is performed by the UAS, the minimum absolute distance cannot be more than 4 NM. In other words, if a separation distance of 5 NM has to be ensured, a *Time to Conflict* of 2 minutes is not enough regardless the Δh value (if the UA to performs the separation maneuver).

Separation Minima	Δh for the UAS t_c [minutes]			Δh for the intruder t_c [minutes]		
	2	5	10	2	5	10
3 NM	40°	15°	5°	15°	5°	5°
5 NM	N/A	25°	15°	20°	10°	5°
10 NM	N/A	N/A	25°	50°	15°	10°

TABLE III
MINIMUM Δh TO ENSURE LATERAL SEPARATION ($\beta = 0^\circ$)

D. Lateral conflicts

We define a lateral conflict as any oblique conflict geometry ($\beta \neq 0^\circ \neq 180^\circ$). As an illustrative example, simulation results for $\beta = 90^\circ$ are depicted in Figure 5. Note that for any oblique conflict geometries y-axis symmetry disappears. Therefore, depending on the conflict geometry, turning left will be better than turning right or vice versa for a given Δh . Table IV shows the minimum Δh to ensure a specific lateral separation minima, assuming that the ATCo commanded aircraft turns in the direction that minimizes the required Δh . As expected, the required Δh is lower than the backward conflict geometry but higher than the forward case.

Summing up, two points have to be taken into account when the speed of two conflicted aircraft are dissimilar. On one hand, it is always better to resolve the conflict in terms of maximization of the minimum absolute separation distance when the fastest aircraft performs the heading change. On the other hand, the minimum absolute distance is strongly related with the conflict geometry, being the worst case the backward one.

III. UAS ORIENTED SEPARATION MANEUVERS

As discussed in the previous section, separation conflicts between a UA and an airliner can be better solved if the last performs the heading change. Yet, if the Time to Conflict (t_c) is big enough, the separation can be totally assured by means of changing the UA heading. There are scenarios where this

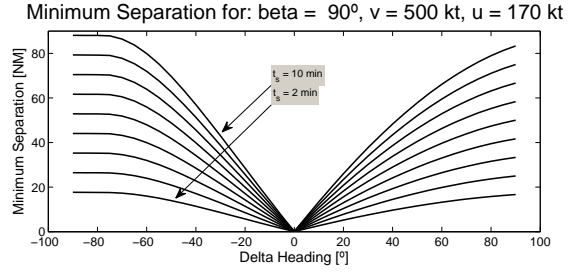
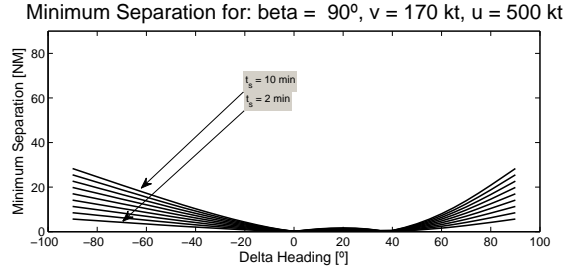


Fig. 5. Lateral conflict in which (a) the UAS performs a separation heading change and, (b) the intruder performs the heading change.

Separation Minima	Δh for the UAS t_c [minutes]			Δh for the intruder t_c [minutes]		
	2	5	10	2	5	10
3 NM	55°	30°	15°	15°	10°	5°
5 NM	85°	40°	25°	25°	10°	5°
10 NM	N/A	70°	40°	35°	15°	10°

TABLE IV
MINIMUM Δh TO ENSURE LATERAL SEPARATION ($\beta = 90^\circ$)

aspect becomes important, such as backward conflicts, when, instead of having only one airliner chasing the UA, we could have several ones that follow the same airway. In this case, it will be easier for the ATCo to command a single heading change to the UA than several commands to all the pursuers. Therefore, it becomes necessary to design UA specific separation maneuvers not only from the geometric point of view, but also from the UAS pilot and ATCo operational situation awareness. This section presents some maneuvers, specific for UAS operations considering both en-route and UAS mission flight phases.

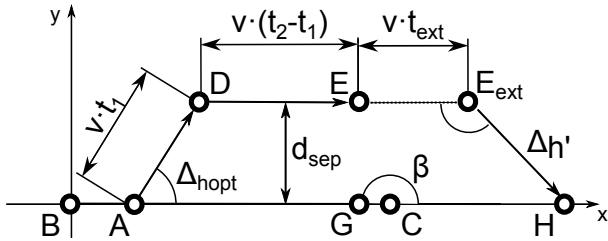


Fig. 6. Proposed separation maneuver for backward conflict geometry.

For the en-route flight phase, and from a geometric point of view, the best way to obtain a minimum lateral separation distance d_{min} is to change the UA heading in such a way that the minimum separation distance is maximized (in this way, the minimum separation value is achieved as soon as possible):

$$\Delta h_{opt} = \arg(\max_{\Delta h} d_{min}(\Delta h)); \quad \Delta h \in [-90^\circ, 90^\circ] \quad (1)$$

For instance, in a forward conflict geometry, $\Delta h_{opt} = \pm 90^\circ$ and for a backward geometry, $\Delta h_{opt} = \pm 65^\circ$ (see Figures 3 and 4 respectively).

Figure 6 depicts the whole separation maneuver regarding to a backward conflict geometry. At the time that the conflict

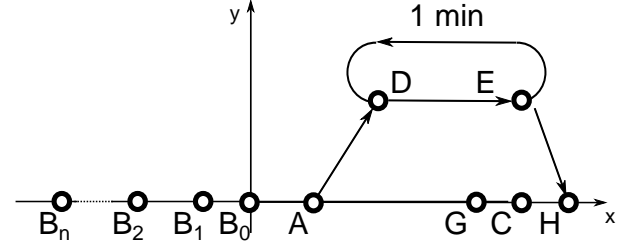


Fig. 7. Modified separation maneuver for backward conflict geometry.

is detected, the UA is located at A point while the airliner is at B . ATCo commands UA to change its heading $\pm \Delta h_{opt}$. At $t = t_1$ the UA will arrive to point D , where the lateral separation d_{sep} is guaranteed. Then, the UA will adapt its trajectory to fly a parallel track with respect to the airliner up to the point that both aircraft have the same x -coordinate ($t = t_2$). The airliner will be in point G and the UA in point E , assuring the minimum lateral separation d_{sep} . Then, the UA will keep the same bearing for a buffer safety time (t_{ext}) before returning to the original flight plan changing its heading to $\Delta h'$.

From an operational point of view, as the suggested maneuver is pre-planned and known beforehand by the ATCo and UAS crew, the situational awareness of both ATCo and UAS pilot-in-command can be significantly improved. Moreover, as the UA is flying in a parallel track with respect to its original flight plan, the negative impact on the missions, in terms of extra distance flown, is mitigated. Let us define $\Delta t = t_2 - t_1$ as the time that the UA flies in this parallel track. From an operational point of view Δt should be bounded to a maximum value. Qualitatively speaking, any Δt resulting from the scenario shown in Figure 6 could be accepted. However, in a scenario with several intruders following the same airway, Δt and therefore, the absolute distance between D and E , could be bigger than desirable.

For this reason, the maneuver depicted in Figure 6 is redefined and a holding pattern for the UA is inserted at the end of the parallel separation track. This hold is defined with a Hold to a Fix (HF) RNAV waypoint located at point E , a hold inbound track parallel to the original UA track and with the outbound holding track on the outer side of the maneuver (see Figure 7). In this way, Δt can be bound to a specific

value (depending on the scenario, UA performances,...) and pre-negotiated with the ATC. If the UAS predicts that the required time in the parallel track is higher than this maximum value, the holding pattern is executed with as many iterations as necessary. As explained before, this strategy would be particularly useful when several intruders are present and the UA can not return to its original flight plan until the conflict with the last intruder is cleared.

In the mission phase, once the separation point D is reached, turning back into the opposite direction may be better in terms of mission disruption. There are several mission tasks (e.g. surveillance, remote sensing, ...) where flying a specific track is crucial for mission results and therefore, the UA cannot simply skip a portion of the flight plan. Figure 8 shows this mission separation maneuver.

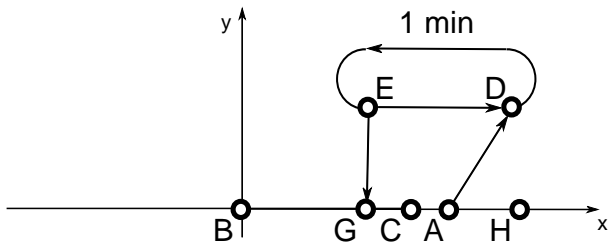


Fig. 8. Modified separation maneuver for backward conflict geometry in mission stage.

Summing up, if en-route, the UAS would prefer to keep its initial heading, as it will take the UA closer to its destination. However, if performing surveillance, any area not overflowed due to the separation maneuver will need to be re-explored after the conflict is cleared. In this way, a backtrack trajectory may allow the UAS to easily reinsert back into its original surveillance track, minimizing the negative impact of the maneuver. Moreover, in the case that multiple intruders appear in sequence the UAS may retain its separation position for longer time by performing a hold pattern that keeps the desired separation with the original track. Hold pattern can be repeated as long as necessary, and it is compatible with both types of maximum separation maneuvers (forward / rear facing separation maneuver).

IV. REAL-TIME SIMULATION ENVIRONMENT

A simulation tool called ISIS has been developed to evaluate multiple aspects of the integration of UAS in non-segregated airspace [19]. ISIS is currently coupled with the X-Plane flight simulation environment, including two UA models based on NASA's Predator-B and Global Hawk (currently used in scientific missions). In order to evaluate the dynamic behavior of the UAS and support UAS-ATC interaction, the simulation environment is integrated with Eurocontrol's eDEP (Early Demonstration and Evaluation Platform) through the interchange of ADS-B messages.

eDEP³ is a low-cost, lightweight, web-enabled ATC simulator platform, offering an environment for rapid prototyping

³<http://www.eurocontrol.fr/projects/edep/>

applications. eDEP includes the core platform functions for airspace management, flight plan preparation, flight management, trajectory prediction, coordination services and flight path monitoring, and provides an EATMP compliant controller working position (CWP), and a graphical pilot working position (PWP); etc. Operational simulations have been conducted by employing traffic available from Eurocontrol.

Within this simulation environment a complete UAS-based surveillance mission is being developed, covering all aspects related to the UAS departure, en-route, mission, arrival, and in-flight contingencies. Figure 9 depicts the main flight plan management interface in which the current UAS flight plan can be tracked, as well as selected parameters updated. The interface also allows to graphically explore contingency alternatives and separation maneuver in real-time. The flight plan depicted in Figure 9 describes a surveillance operation that departs and returns from LEBL and performs an extensive scanning operation over the Pyrenees range. The mission follows an iterative scheme that starts with a holding operation near the surveillance area. Once ATC clearances are obtained, the UAS starts a repetitive scanning operation that returns to the holding area awaiting for the command to repeat another scan or the command to return to LEBL.

Conflicts generated due to the insertion of the simulated UAS into the European airspace while being simulated by eDEP can be seen in Figure 10. The UAS awareness system (on the right) detects the intruder through the incoming ADS-B messages so that the best suited separation maneuver can be selected. At the same time, the ATCo position in eDEP (on the left) permits to visualize the development of the separation conflict using both the tactical and strategic tools typically available to them. According to the separation conflict, the pilot may command a heading change (requested by the ATCo) or propose the maximum separation maneuver discussed in previous sections.

ISIS (see Figure 11) includes an HMI interface designed to support the separation maneuver selection. The pilot can preview two different maneuvers at the same time and update their parameters in real time. Once a maneuver is selected it must be committed so that the UAS executes it and later returns to the nominal flight plan. Flight time estimation is also computed so that the geometry of the separation conflict can be re-evaluated. Both forward and backward separation maneuvers are available. Maximum separation, dimensions of the holding pattern, number of iterations (from 0 to N), right/left turn, and altitude change can be tailored to the separation requirements. The geometry any selected maneuver and the incoming conflict is recomputed every second so that the pilot may have enough time and information to properly evaluate the situation and react to ATC requests. As seen in Figure 10, the interface offers information about the conflicting traffic, the area in which the intrusion will occur given the intentions of both aircraft, and predictions of the committed separation maneuver.

The execution of both types of separation maneuvers is shown in Figure 11. Both trajectories perform the planned

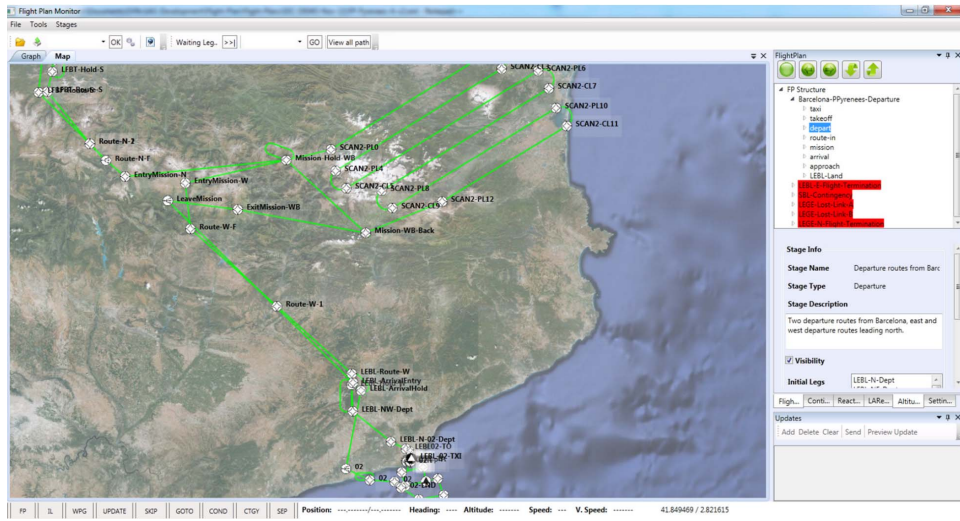


Fig. 9. Screenshot of the Flight Plan Management interface in the USAL architecture. The depicted flight plan is used as an example and represents a typical fire surveillance mission over the Pyrenees range, departing from Barcelona's airport (LEBL).

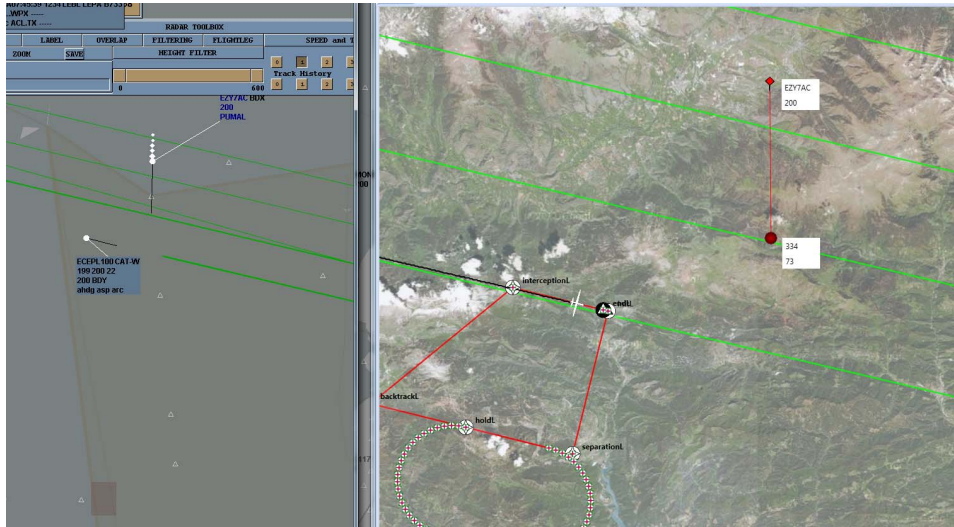


Fig. 10. Separation conflict and maneuver as seen in both eDEP and ISIS.

maximum separation turn that it is immediately sequenced with a single iteration racetrack. Once completed, the backwards maneuver re-inserts the UAS in the original track, while the forward facing maneuver re-inserts the UAS much latter in the flight plan.

The soundness of the concept is currently being evaluated through the generation of a significant number of simulation scenarios that will include different UA speeds, turning capabilities, conflicting angles pilot reaction time and amount of traffic. The objective is to gather experimental data to fully understand the limitations and impact that the proposed maneuvers may have on both the UA pilot, the ATCo and the surrounding traffic. Realistic scenarios are being currently implemented so that experienced ATCo's could be confronted with them and complete the evaluation process.

V. CONCLUSION AND FURTHER WORK

Achieving continual safe separation distances between all aircraft is a critical requirement for integrating UAS and manned aircraft within controlled and uncontrolled airspace. This paper has evaluated simple conflict scenarios between a MALE UA and a jet airliner intruder, when both aircraft remain at the same altitude and separation is guaranteed by changing the heading of only one of both aircraft. Results show that the minimum horizontal separation distance is strongly dependent to the relative velocity between the conflicting aircraft. Given that the cruise airspeeds differences between airliners and UA are huge, we have determined that separation (if executed by the UA) needs to be executed much more in advance and more aggressively than currently employed vectoring-based maneuvers.

Based on this result, the paper has introduced a set of

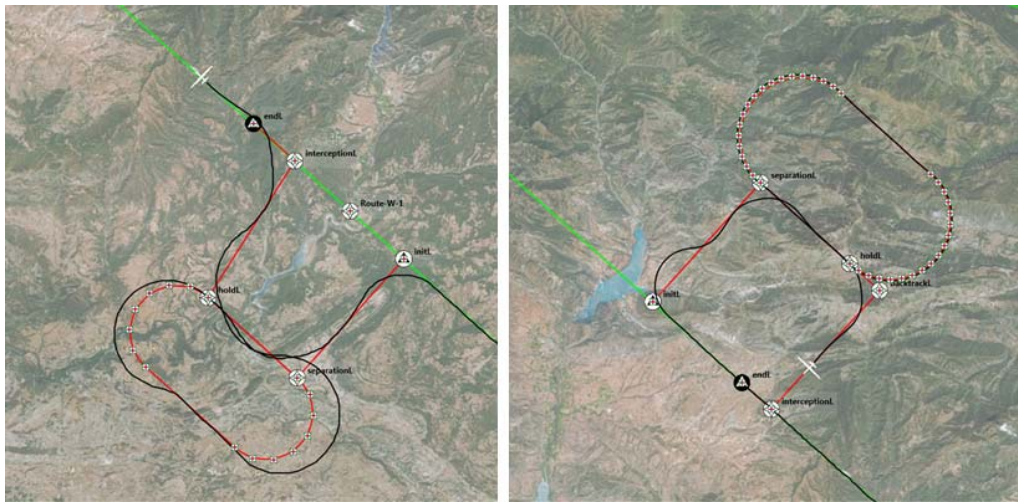


Fig. 11. Forward and backwards separation maneuvers as seen in the ISIS simulation environment.

pre-planned separation maneuvers to be employed by the UA. These maneuvers can guarantee the maximum separation rate while minimizing the negative impact on a hypothetical surveillance mission of the UAS. The soundness of the concept has been validated in a real-time simulation environment that combines a detailed UA operation with a air traffic simulation environment. Initial experiments indicate the feasibility of the concept, although additional experiments need to be developed in order to determine the real impact of the UA's performance, the workload for the ATCo and the potential impact on surrounding traffic.

ACKNOWLEDGMENTS

This work has been partially funded by Ministry of Science and Education of Spain under contract CICYT TIN2010-18989. This work has been also co-financed by the European Organization for the Safety of Air Navigation (EUROCONTROL) under its CARE INO III programme. The content of the work does not necessarily reflect the official position of EUROCONTROL on the matter.

REFERENCES

- [1] P. Brooker, "Air traffic control separation minima: Part 1 the current stasis," *Journal of navigation*, vol. 64, pp. 449–465, 2011.
- [2] J. Kuchar and L. C. Yang, "A review of conflict detection and resolution modeling methods," *IEEE Transactions on Intelligent Transportation Systems*, vol. 1, no. 4, pp. 179–189, Dec 2000.
- [3] Eurocontrol, "Operational Requirements Document for EATCHIP Phase III. ATM Added Functions. Volume 5 - Medium Term Conflict Detection," Eurocontrol, Tech. Rep., January 1999, document OPR.ET1.ST04.DEL01.5.
- [4] —, "Review of asas applications studied in europe," CARE/ASAS Action. CARE/ASAS Activity 4, Technical report, Feb 2002, available at: <http://www.eurocontrol.int/care-asas/gallery/content/public/docs/act4/care-asas-a4-02-037.pdf>.
- [5] G. Bartkiewicz, "Enhancement of airborne conflict prediction times through automatic dependent surveillance-broadcast (ADS-B) transmitted trajectory intent information," in *Proceedings of the 20th Conference on Digital Avionics Systems (DASC)*, vol. 2. AIAA, oct 2001, pp. 7B1/1–7B1/11.
- [6] S. Tenoort, "Concept for civil uasapplications," INOUI: Innovative Operational UAS Integration, Tech. Rep., May 2008, tech. Rep. D1.2.,
- [7] UAVNET, "European civil unmanned air vehicle roadmap, volumes 1 and 2," Available on-line at: <http://www.uavnet.com>, 2005.
- [8] K. Dalamagkidis, K. P. Valavanis, and L. A. Pieggl, *On integrating unmanned aircraft systems into the national airspace system: issues, challenges, operational restrictions, certification and recommendations*, ser. International series on intelligent systems, control, and automation: science and engineering, S. G. Tzafestas, Ed. Springer-Verlag, 2009, vol. 26.
- [9] B. Papadales and M. Downing, "UAV science missions: A business perspective," in *Proceedings of the Infotech@Aerospace conference*, Arlington, Virginia, 2005.
- [10] S. Graham, W. Chen, J. De Luca, M. Kay, J. and Deschenes, V. Weingarten, N. and Raska, and X. Lee, "Multiple intruder autonomous avoidance flight test," in *Proceedings of the AIAA Infotech@Aerospace Technical Conference*. St. Louis, Missouri (USA): AIAA, Mar 2011, paper No 2011-1420.
- [11] D. Alejo, R. Conde, J. Cobano, and A. Ollero, "Multi-UAV collision avoidance with separation assurance under uncertainties," in *Proceedings of the IEEE International Conference on Mechatronics (ICM 2009)*. Malaga, Spain: IEEE, April 2009, pp. 1–6.
- [12] G. Spence, D. Allerton, R. Baumeister, and R. Estowski, "Real-time simulation of a distributed conflict resolution algorithm," in *Proceedings of the 26th Congress of the International Council of the Aeronautical Sciences (ICAS)*, Anchorage, Alaska (USA), Sep 2008.
- [13] G. Doweck and C. Muoz, "Conflict detection and resolution for 1,2,...,N aircraft," in *Proceedings of the 7th AIAA aviation technology, integration and operations conference*. AIAA, Sep 2007.
- [14] C. Carbone, U. Ciniglio, F. Corrado, and S. Luongo, "A novel 3d geometric algorithm for aircraft autonomous collision avoidance," in *Proceedings of the 45th IEEE Conference on Decision and Control*. IEEE, Dec 2006, pp. 13–15.
- [15] S. J. Cho, D. S. Jang, , and M. J. Tahk, "Application of TCAS-II for unmanned aerial vehicles," in *Proceedings of JSASS-KSASS Joint Symposium on Aerospace Engineering*, Nagoya, Japan, Oct 2005.
- [16] S. Han and H. Bang, "Proportional navigation-based optimal collision avoidance for uavs," in *Proceedings of the 2nd International Conference on Autonomous Robots and Agents*, Dec 2004.
- [17] ICAO, *Procedures for Air Navigation Services. Air Traffic Management*, 14th ed., International Civil Aviation Organisation, Montreal (Canada), 2001, doc. 4444.
- [18] X. Prats, L. Delgado, J. Ramrez, P. Royo, and E. Pastor, "On the possible requirements for sense and avoid in uas: issues and challenges," *Journal of Aircraft*, In press.
- [19] E. Pastor, P. Royo, M. Prez-Battle, X. Prats, and C. Barrado, "Evaluating technologies and mechanisms for the automated/autonomous operation of UAS in non-segregated airspace," in *Proceedings of the First SESAR Innovation Days, 29th*. Toulouse, France: SESAR, Nov 2011.