

# A Taxonomy of UAS Separation Maneuvers and their Automated Execution

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## ABSTRACT

This paper proposes to create a taxonomy of separation conflicts between Unmanned Aerial Systems (UAS) and intruding aircrafts to facilitate its insertion in non-segregated airspace. The classification is created according to the relative speeds, angular geometry, initial intent, etc. A catalog of separation maneuvers that best fit each scenario is introduced and evaluated through a real-time simulation environment. This advisory mechanism will benefit both the UAS pilot and the ATCo in order to negotiate the best suited separation maneuver. Eventually, the same strategy can be employed as an autonomous separation system on-board a UAS that suffers a lost-link contingency, alleviating its negative impact in the airspace.

## Categories and Subject Descriptors

J.2 [Physical Sciences and Engineering]: *Aerospace*.

## General Terms

Documentation.

## Keywords

UAS automation, Airspace integration, Separation conflicts.

## 1. INTRODUCTION

In aviation, two main functionalities are employed to minimize the probability of collision with other aircraft: 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. As an additional safety layer, collision avoidance can prevent an imminent collision in case of a loss of separation as a last resort maneuver.

Manned aviation already implements some Airborne Collision Avoidance Systems (ACAS), such as the Traffic Collision Avoidance System (TCAS). 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].

Other collision avoidance systems, 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.

On top of the ACAS systems, separation in controlled airspace is typically responsibility of the ATCo, which issue clearances to the aircraft in order to maintain minimum separation values. Some systems, 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 (MTCDD) 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 from controllers to pilots [4].

During the last decade, the interest of using Unmanned Aerial Systems (UAS) for civil missions and applications has increased significantly [6]. Yet, the lack of a regulation basis concerning their certification, airworthiness and operations is still banning them into non-segregated airspace [7]. Among all UAS applications, surveillance missions will be perhaps the most numerous [9].

Most 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. Additionally, peculiarities like communication latencies and, in the worst case, the loss of data-link with the UAS should also be considered.

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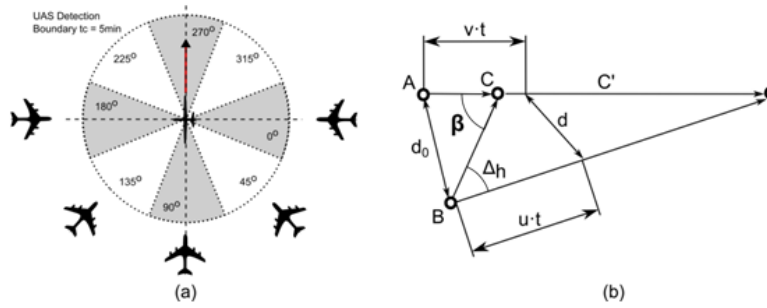


Figure 1: Overview of the UAS separation conflict geometries.

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 [8-14]; few researchers have addressed the separation problem for UAS. Some proposals indeed, implement separation minima in their algorithms (like for instance [9]), but they are in general focused in very small UAS and typical separation values are in the order of meters. Yet, if larger UAS are expected to fly into non-segregated airspace, ICAO compliant separation values (such as 5 NM) have to be addressed [15].

This work focuses on the evaluation of separation maneuvers for UAS and analyzes a number of scenarios where a UAS enters in conflict with a much faster airplane flying at similar altitudes (see Figure 1(a) for an overview of the considered scenarios). 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.

The evaluation of separation conflicts according to the speeds, angular geometry, initial intent, etc.; allows us to determine that the classical vector-based separation maneuvers may not be sufficient for a wide spectrum of conflict configurations. Moreover, vector-based maneuvers may have an extremely negative impact on the UAS mission. As a result this paper introduces and evaluates a catalog of separation maneuvers, classifying the most suitable one for each conflict configuration, thus proposing a reaction taxonomy.

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 will be validated in a real-time simulation environment that combines a detailed UAS operation with an air traffic simulation environment. Initial experiments indicate the feasibility of the concept, although additional experiments need to be developed in order to determine the workload for the ATCo and the potential impact on surrounding traffic.

Once properly evaluated this taxonomy may become an automated advisory mechanism that can benefit both the pilot and the ATCo in order to negotiate the best suited

separation maneuver. In a long term scenario this mechanism may even become partially/fully autonomous in case UAS separation capabilities need to be considered to support lost-link or high latency communication situations.

**2. SEPARATION CONFLICT GEOMETRIES**

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 UAS and conventional airliners may occur. Such conflict geometries need to take into account the notable differences in flight performance between the UAS and such an intruder. It might happen that changing the UAS flight level, in order to maintain separation, would not be a possible solution due to the poor climbing or descending performance of the UAS at cruise altitudes. Similarly, changing the UAS heading will have to be executed well in advance if the UAS is flying at a speed significantly slower than the intruder.

This section evaluates a number of simple conflict scenarios between a typical MALE UAS (a GA MQ-9 Reaper<sup>1</sup> 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.

**Conflict and aircraft performance models**

Figure 1(b) summarizes a simplified conflict geometry used in this paper. An airliner is located in point A. We assume that it is flying at a constant speed  $v$  and altitude. At the same time a UAS is placed at point B. We will also consider that it is flying at a constant speed  $u$  and at conflicting altitude with the airliner. Both aircraft are moving towards the same position in space (point C).

<sup>1</sup> performances obtained from <http://www.globalsecurity.org/intell/systems/predatorb.htm>

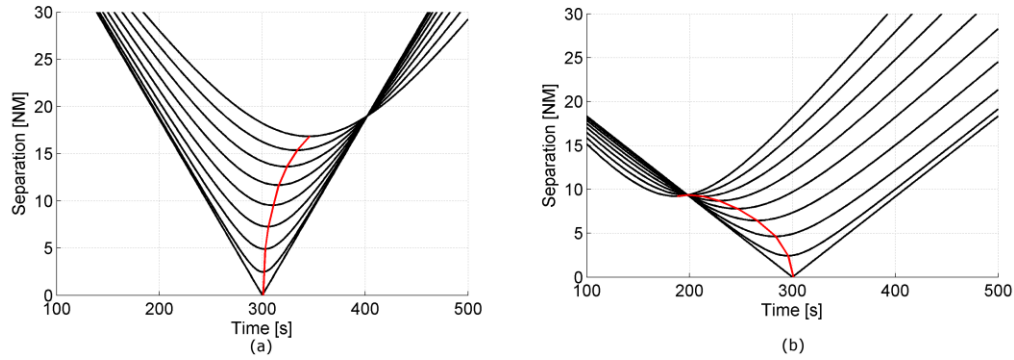


Figure 2: Separation geometries for a maneuvering UAS with conflict angles at  $180^\circ$  and  $0^\circ$ .

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 the UAS (placed in  $B$ ) to change its heading ( $\Delta h$ ). We want to know which is the minimum absolute distance between both aircraft  $d_{sep}$ , along their flight paths, as a function of  $\Delta h$ . 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 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  $C$ ).

Regarding to the performance model, only the speed of each aircraft (at the considered altitude) has been taken into account. An Airbus A320 with cruise speed of 500 kt and a Predator-B with cruise speed of 170 kt are considered.

#### Forward separation conflicts

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

Our analysis for this scenario is shown in Figure 2(a). The plot exposes the simulation results when the UAS performs the separation heading change (either left or right). The x-axis plots the time since the conflict has been detected normalized to a fixed time to conflict of 5 minutes) while, in the y-axis, the minimum absolute distance between aircraft is depicted. Each line represents a different heading change discretized in steps of  $10^\circ$  (from  $0^\circ$  up to  $90^\circ$ ).

As expected, the higher  $\Delta h$ , the larger minimum separation distance achieved (indicated by the perpendicular segment crossing all curves). At least a  $\Delta h = 50^\circ$  heading change is necessary to achieve a minimum separation distance of 10 NM. Even if a  $\Delta h = 90^\circ$  is applied the maximum separation minima that can be guaranteed is well below 20 NM.

#### Backward separation conflicts

We define a backward conflict as a particular case of the conflict model, when  $\beta \approx 0^\circ$ . In contrast to the previous case, both aircraft have the same heading. Therefore, the fastest airliner will move towards the UAS, chasing it, with the minimum possible relative speed between them. Figure

2(b) shows the simulation results for this case when the UAS performs the separation heading change (either left or right). If a lateral separation of 5 NM is required, and the conflict has been detected 5 minutes in advance, a minimum heading change of  $\Delta h = 30^\circ$  is necessary if the ATCo commanded the UAS to perform the separation maneuver. However, if a separation of 10 NM is necessary, not even a  $\Delta h = 90^\circ$  will provide such separation minima.

Backward conflicts are more stringent and some conflict geometries may become unsolvable. If the ATCo commands a separation maneuver with shorter look ahead time, e.g.  $t_c = 2$  minutes (the typical STCA look ahead time), the minimum separation distance between both aircraft cannot be achieved regardless the selected  $\Delta h$ .

#### Lateral separation conflicts

We define a lateral conflict as any oblique conflict geometry such that  $\beta \approx 90^\circ$  or  $\beta \approx 270^\circ$ . Both conflict geometries are equivalent being the only relevant factor the direction in which the UAS is going to turn, to face the incoming intruder or away from it. The resulting analysis is shown in Figure 3, where the UAS turns facing the intruder in 3(a), and away from the intruder 3(b), regardless of  $\beta$ .

Note that for any oblique conflict geometries y-axis symmetry disappears. Therefore, depending on the conflict geometry, turning towards the conflict may be better than turning away from it or vice versa for a given  $\Delta h$ .

Figure 3(b) clearly shows that turning away from the conflicts does not provide any valuable separation until heading change of  $\Delta h \approx 60^\circ$ , in which a 5 NM separation is almost achieved. Values closer to 10 NM can only be achieved with  $\Delta h \approx 90^\circ$ . On the other side, Figure 3(a) shows that by turning against the conflict with  $\Delta h \approx 40^\circ$ , allows to achieve something closer to the 5 NM separation limit, while 10 NM can only be achieved with  $\Delta h \approx 70^\circ$ .

#### Oblique separation conflicts

We define an oblique conflict as any conflict geometry such that  $\beta \approx 45^\circ$  or  $\beta \approx 135^\circ$  (and the symmetric counterparts  $\beta \approx 315^\circ$  or  $\beta \approx 225^\circ$ ). Note that again, there are large separation differences if turning towards the conflict or away from the conflict. In this case only the optimal solution is analyzed.

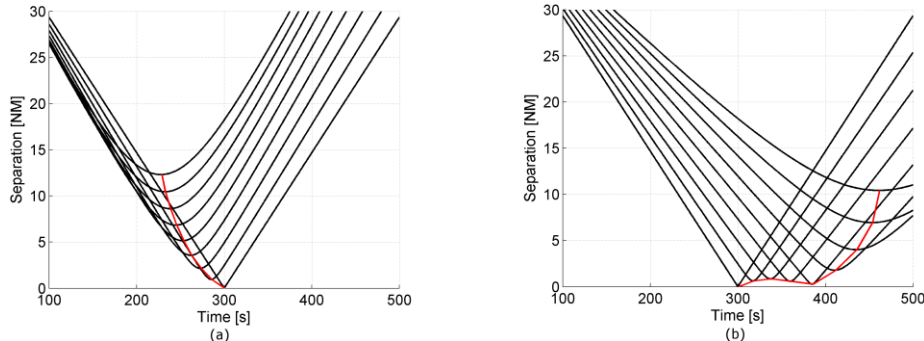


Figure 3: Separation geometries for a maneuvering UAS with conflict angles at  $90^\circ$  turning facing the intruder and  $90^\circ$  turning away from the intruder.

Figure 4(a) shows the resulting scenario for  $\beta \approx 45^\circ$ , in which the UAS turns away from the intruder. In this scenario, small changes in heading provide a rapid increase in the minimum separation; i.e. 5 NM separations can be achieved with  $\Delta h \approx 30^\circ$ , and a 10 NM separation is achievable with  $\Delta h \approx 50^\circ$ . Figure 5 depicts the same results when the UAS turns to the opposite direction. As it can be clearly seen separation values are not sufficient to guarantee the safety of the operation.

### 3. TAXONOMY OF UAS SEPARATION MANEUVERS

Separation conflicts between a UAS and an airliner can be better solved if the last performs the heading change due to its better performance parameters. Only in the case that the Time to Conflict is big enough, the separation can be totally assured by means of changing the UAS heading.

Moreover, there are specific scenarios where this aspect becomes important, such as backward conflicts, when, instead of having only one airliner chasing the UAS, 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 UAS than disrupting the trajectory of all the pursuers.

Given the UAS performance limitations and mission constraints it becomes obvious that it is necessary to design UAS specific separation maneuvers for all possible geometric configurations, but also from the UAS pilot and ATCo situational awareness. This section presents or selection of separation maneuvers, specific for UAS considering both en-route and UAS mission flight phases.

#### General strategy

Our proposal strictly focuses on separation maneuvers in which the UAS performs the heading change. Separation minima of 10 NM will be targeted based on a time to conflict of 5 min. Although standard separations fall in the 3/5 NM range, 10 NM is employed as a way to cover the UAS turning limitations, communication latencies and decision time. Future work will fully addresses this factors, but then the 3/5 NM range will be targeted (unless rulemaking decisions specify that UAS require wider separations than manned aviation). The time to conflict range is used as a uniform way to treat conflict detection ranges, and it is fully compatible with the strategy

employed to specify the ADS-B MASPS [16].

#### Forward and backward separation maneuvers

For the en-route flight phase, and from a geometric point of view, the best way to obtain proper lateral separation is to change the UAS 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).

Both the forward conflict geometry,  $\beta \approx 180^\circ$  and the backward conflict geometry,  $\beta \approx 0^\circ$  are clear representatives of this scenario (recall Figure 2).

If a 10 NM separation needs to be guaranteed, the forward separation conflict requires a heading change of around  $\Delta h \approx 50^\circ$ , while the backward conflict requires a maximum separation maneuver  $\Delta h \approx 90^\circ$  to barely achieve 8-9 NM.

Under these circumstances for both  $\beta \approx 180^\circ$   $\beta \approx 0^\circ$ , Figure 6(a) describes our proposed separation maneuver. An almost maximum turn maneuver is prescribed until the UAS reached a position  $D$  that guarantees the required separation ( $d_{sep}$ ). A heading change  $\Delta h \approx 90^\circ$  is generally required, although it could be more relaxed in case of a forward conflict. Once position  $D$  is reached, the UAS will turn again following its original track until a position  $E$  is reached in which the conflict is cleared. Then, the UAS will keep the same heading for a buffer safety time (reaching  $E_{ext}$ ) before returning to the original flight plan by changing its heading to a value  $\Delta h' < 90^\circ$ . Both the cleared conflict position  $E$  and its safety extension will strongly depend on the orientation of the conflict and the targeted separation.

Note that if  $\beta \neq 180^\circ$  or  $\beta \neq 0^\circ$ , the separation maneuver needs to be executed either right range of or left according to the direction that maximizes the separation distance that will be obtained once point  $D$  is reached. Moreover, later in the section we will identify which conflict angles ( $\beta$ ) will be considered as forward/backward conflicts.

Given this basic separation maneuver, operational deficiencies may rise due to the peculiarities of the UAS performance and its operational nature.

Forward and backward separation conflicts are most likely due to the operation of a UAS over an airway. Airliners operate on busy airways with well-defined timed separations, designed according to the homogenous cruise

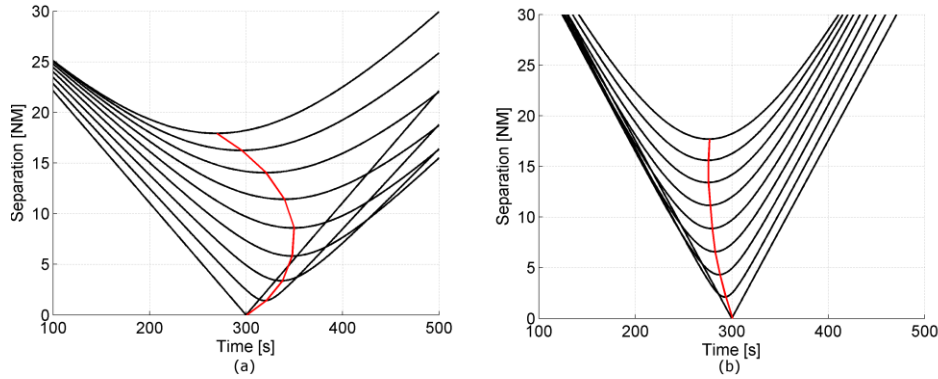


Figure 4: Separation geometries for a maneuvering UAS with conflict angles at  $45^\circ$  and  $135^\circ$ .

performance that most of them exhibit. In case a UAS faces a separation conflict with multiple airliners, it may not be reasonable to force the UAS to maintain a separation track longer than certain values. Most likely the UAS would like to stick to the original track because its mission may be directly related to the capacity of perform surveillance on that specific area. If this is the case, Figure 6(a) also depicts two alternative procedures that may be more beneficial to the UAS operation.

Instead of following a track parallel to the original route, the UAS may enter a holding track while maintain the desired safety separation. This holding track may be executed following the original UAS heading (in this case the forward conflict will be cleared earlier); or following a reverse course (now the backward conflict will be cleared earlier). The optimality of the maneuver fully depends on the original UAS mission and on the fact that the fragment of the original flight plan that will be left unexplored needs to be re-explored.

**Oblique separation maneuvers**

Both forward and backward oblique conflicts require a variable heading change relative to the angle  $\beta$  of the incoming intruder. In order to provide a generalized separation solution; but also to clearly identify the limits of  $\beta$  that can be considered as oblique, lateral or forward/backward, a uniform separation strategy is being considered. This common strategy is depicted in Figure 6(b) for forward oblique conflicts, while Figure 6(c) depicts the same strategy for backward oblique conflicts.

The separation strategy as depicted in Figure 6(b) suggests that the UAS will turn towards the intruder with a heading change  $\Delta h$  equivalent to the angle of conflict  $\beta$ . The result is that the UAS will take a parallel track to the intruder, in which the separation between both tracks will depend on the angle  $\beta$  and on the point in which the separation is initiated (here assumed instantaneous). Note that under our specific scenario ( $t_c = 5$  min and relative speed between both aircraft), the UAS distance to the conflict point is around 14.16 NM.

The separation maneuver makes the UAS to turn towards the conflict and keep a parallel track until a point E is reached in which the conflict is cleared. A certain safety

margin is added by extending the track until  $E_{ext}$  is reached. Then the UAS may turn directly to the original track, or it may extend some additional safety margin following the initial heading before heading back to the original track.

According to the conflict angle and specific speeds two critical factors need to be identified in order to guarantee the safety of the maneuver:

1. The minimum separation distance ( $d_{min}$ ).
2. Time to reach  $d_{min}$  and thus to clear the conflict.

Figure 7 shows minimum separation distance that can be achieved related to the UAS heading change and the selected time to conflict. The shaded area corresponds to the acceptable heading changes when a given minimum separation needs to be guaranteed, assuming a  $t_c$  of 5 minutes. The remaining curves specify the same relationship for different  $t_c$  values.

The results show that to guarantee a 10 NM minimum separation the heading change ( $\Delta h$ ) may range between  $40^\circ$  to  $90^\circ$ ; that is, oblique separation conflicts can be safely cleared with the proposed maneuver if the conflict angle  $\beta$  is within the  $[90^\circ-140^\circ]$  range. Conflicts with  $\beta$  within the  $[140^\circ-180^\circ]$  range need to be considered as forward conflicts and the maneuvers described in Figure 6(a) apply.

The same principle applies for backward conflicts as shown in Figure 6(c). Here, both  $\beta$  and  $\Delta h$  are equivalent; thus, valid ranges for oblique backward conflicts lay within the  $[40^\circ-90^\circ]$  interval; while pure backward conflicts need to be considered in the  $[0^\circ-40^\circ]$  interval.

Once angular ranges have been determined, we have to identify the time required to reach the minimum separation distance. This time determines a safety minimum in order to clear the conflict and then proceed back into the original flight plan. However, the time to  $d_{min}$  is not symmetrical for both forward and backward conflicts as seen in Figure 8.

Figures 8(a) and (b) describe the time to  $d_{min}$  corresponding to the maneuver scenarios described in Figures 6(b) and 6(c) respectively. Figure 8(a) demonstrates that the time to  $d_{min}$  progressively decreases when the heading change  $\Delta h$  increases. For the limit case in which  $\Delta h \approx 90^\circ$ , the intruded will be cleared in just over 3.7 minutes, but if  $\Delta h \approx 60^\circ$  the conflict will only be cleared after 4.4 minutes. Obviously

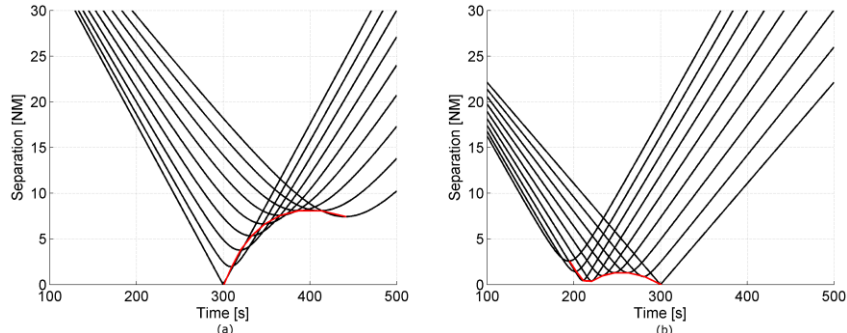


Figure 5: Separation geometries for a maneuvering UAS with conflict angles at  $45^\circ$  and  $135^\circ$  responding on the opposite side than the separation maneuver described in Figure 4.

the time required to clear the conflict depends on the relative speed of both aircraft. Figure 8(a) depicts value ranges for our standard intruder flying at 500 kt, but also for slower intruders down to the 300 kt range. In case an oblique backward conflict exists, Figure 8(b) shows that the time to  $d_{min}$  progressively increases with the heading change  $\Delta h$ . Again, for the limit case in which  $\Delta h \approx 90^\circ$ , the intruder can be cleared only after well over 7.5 minutes, but if  $\Delta h \approx 60^\circ$  the conflict be cleared after 6.2 minutes. As in Figure 8(a), different speed ranges are shown, from the 500 kt basic value down to 300 kt. In that case it can be appreciated that the geometry is much more sensitive to speed variation as the relative speed between the conflicting aircraft is greatly reduced.

**Lateral separation maneuvers**

Oblique conflicts in which the conflict angle is close to  $\beta \approx 90^\circ$  are identified as lateral conflicts, and represent a different class of separation conflict in itself. Applying the separation maneuver employed for oblique conflicts requires the UAS to perform a radical heading change that may have a negative impact on the UAS mission. Moreover, keeping the UAS under this new heading until the conflict is cleared may greatly separate the UAS from its initial trajectory. However, the numerical analysis performed so far demonstrates that in this type of conflict the UAS is well clear of the path of the intruder, up to 14 NM to the collision point for a 5 min time to conflict.

Moreover, if the  $\Delta h \approx 90^\circ$  separation maneuver is executed,

the UAS will travel up to 3.3 minutes until the conflict is cleared (maybe 4 minutes to add some security margin). In that case the UAS will separate more than 11 NM from its original track. Deriving alternative maneuvers for lateral conflicts may reduce the negative impact on the original trajectory and on the surrounding traffic, as the UAS may keep closer to its initial intentions.

Figure 9 outlines our proposed strategy for lateral conflicts. The objective is to keep the UAS well-clear of the intruder path, thus a 10 NM boundary may be created between any UAS maneuver and the flight plan of the airliner. Without trespassing this boundary the UAS may execute a holding maneuver that delays its forward movement (in the future speed modifications may be also combined to reduce the total amount of involved maneuvering). As described in the figure, the UAS has two alternatives: (1) it may perform a left-turn holding track overlapped to its initial trajectory waiting the conflict to be cleared (at least 5 minutes will be necessary). (2) Or it may perform a similar holding track turning towards the incoming intruder. In that case the time to conflict may be slightly reduced (maybe around 1 minute); thus the UAS may proceed forward earlier and later on turn progressively to retake its original track. In both cases the amount of maneuvering is increased, but overall the negative impact on the UAS mission will be reduced as the vehicle may remain closer to its intended surveillance area.

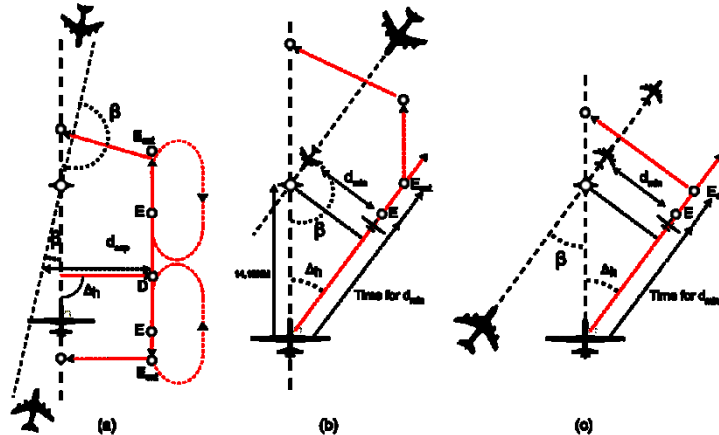


Figure 6: Maneuvers for (a) forward and backward conflicts, (b) forward oblique conflict and (c) backward oblique conflict.

**4. UAS AUTONOMY AND SAFETY MARGINS**

This research assumes that the UAS always performs the separation maneuver. However, UAS maneuvering for separation has two limiting factors that need to be taken into account: (1) the complexity of the conflict-detection and maneuver-decision process due to the remote nature of the operation; and (2) the limited UAS turning capability.

Figure 10 outlines the main elements that affect the separation-decision process in a UAS system. First of all, the separation conflict detection may take place onboard the UAS thanks to the ADS-B technology; or on the ground thanks to ADS-C, ATC radar or any future service available through SWIM technology. Conflict detection and the identification of the optimum separation maneuver may happen both on the air and on the ground.

Messages should be sent from the UAS avionics down to the control station notifying the separation conflicts and the separation advisories generated by the onboard avionics. UAS information needs to be correlated to any ground-based source to guarantee its coherence. Only then a valid resolution may be taken by the pilot. This separation resolution must be notified to the UAS as soon as possible so that the separation maneuver is initiated.

Overall, additional latency due to communication delays will happen. This delay needs to be added to the inherent turning limitations of the UAS and the pilot resolution time under a limited-awareness environment.

UAS communication delays introduce a new dimension due to the possibility of a permanent/temporal loss of the command&control link between the pilot and the UAS. It is our believe that the UAS avionics needs to monitor the pilot's response time and autonomously apply the separation resolution computed onboard if no response is received in a reasonable time period.

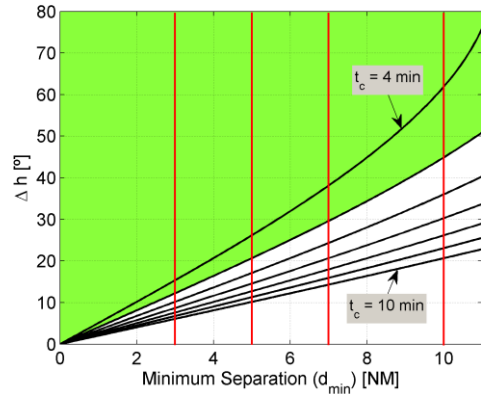


Figure 7: Minimum separation distance related to the heading change when a parallel track is selected.

In case a well-identified lost-link occurs, it may be decided that the UAS will not perform any autonomous separation maneuver. Autonomous separation will add additional uncertainty to the UAS flight-path, which is highly undesired. In that case, with a UAS under a declared emergency, the ATCo may command the intruder to initiate the separation maneuver. However, a lost-link or a temporal communication glitch may happen at any time, which may become catastrophic if it is combined with a separation conflict.

The limited turning capability of the UAS comes into help in this situation. As Figure 11 demonstrates when the high speed intruder maneuvers to avoid the separation conflict, higher separation values are achieved in less time and with limited heading changes. Overall, if a separation conflict occurs combined with an unexpected lost link scenario and additional safety margin exits so that the manned intruder

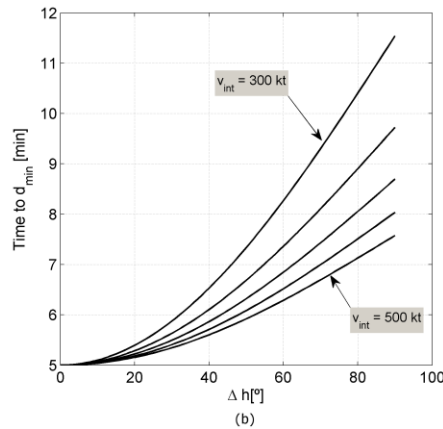
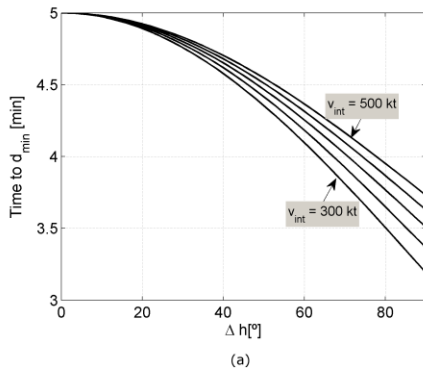


Figure 8: Time to reach the minimum separation distance according to the UAS heading change for (a) forward oblique conflicts and (b) backward oblique conflicts.

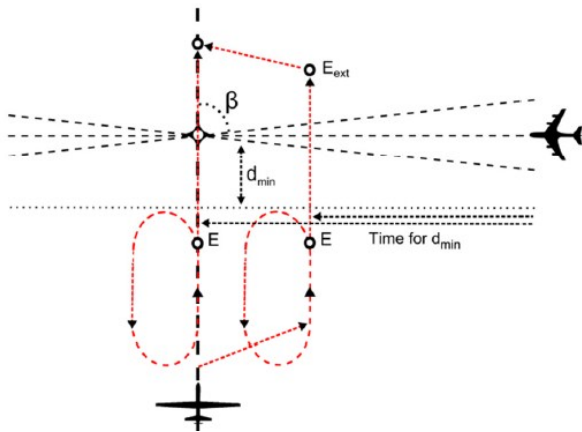


Figure 9: Strategy for lateral conflicts in which the UAS minimizes its deviation from the original track.

can still be commanded to initiate a safe separation maneuver. Further analysis is required to identify the exact time margins available for each conflict geometry.

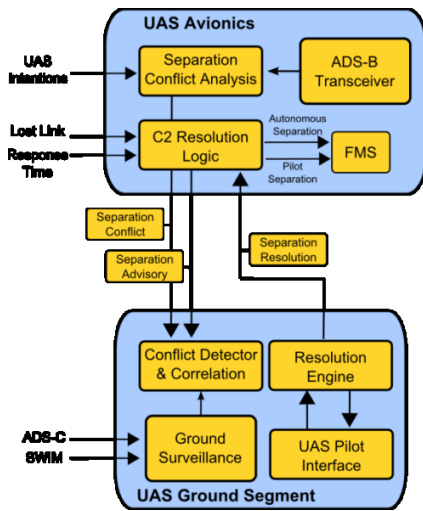


Figure 10: Conflict detection and separation decision process in a UAS system.

5. EXPERIMENTAL EVALUATION

Conflicts generated due to the insertion of UAS into non-segregated airspace while being simulated by a combination of a real-time UAS simulation environment called ISIS and Eurocontrol's eDEP (Early Demonstration and Evaluation Platform) ATC simulation tool. Figure 12 depicts a sequence of conflicting traffic used as test benchmark that the simulated UAS needs to negotiate.

In this environment the UAS awareness system detects the intruder through the incoming ADS-B/C messages so that the best suited separation maneuver can be selected by the UAS pilot. At the same time, the ATCo position in eDEP permits to visualize the development of the separation conflict using both the tactical and strategic tools typically available to them.

ISIS includes a Human Machine Interface (HMI) to support the separation maneuver selection (see Figure 13). The

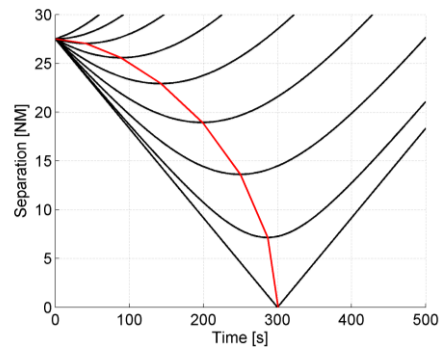


Figure 11: Separation geometry for maneuvering intruder with conflict angle at 0°.

pilot can preview two different maneuvers 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. Maximum separation, dimensions of the holding pattern, number of iterations for holding tracks (from 0 to N), right/left turn can be trimmed to requirements. The geometry and the incoming conflict is recomputed every second so that the pilot has enough time and information to properly evaluate the situation and react to ATCo requests.

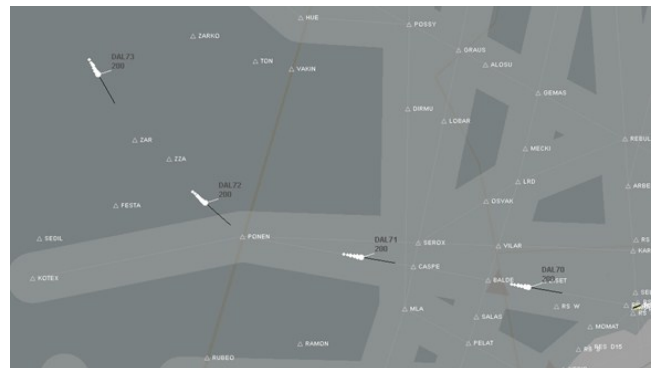


Figure 12: Conflicting traffic in the eDEP visual interface.

Figure 14 depicts a number of conflict situations as seen from the ISIS visual interface. In these images the UAS performs different maneuvers. For the forward conflicts, the UAS is turning right in order to enter into a holding track while maintain the desired safety separation. In this case, the holding track is executed following the original UAS course. The UAS keeps in the holding pattern letting several conflicting aircrafts to go by while keeping the desired safety separation (6NM). Figure 15 shows as the separation between aircrafts decreases for DAL0, increases for DAL1 as the UAS is on the other side of the holding pattern, and returns to the minimum safety values for DAL2. In case of a backward conflict, the UAS turns right to gain separation, and enters a holding pattern in a reverse course. Figure 15 shows that no maneuver was executed to avoid DAL0, while both DAL1 and DAL2 are maintained within the



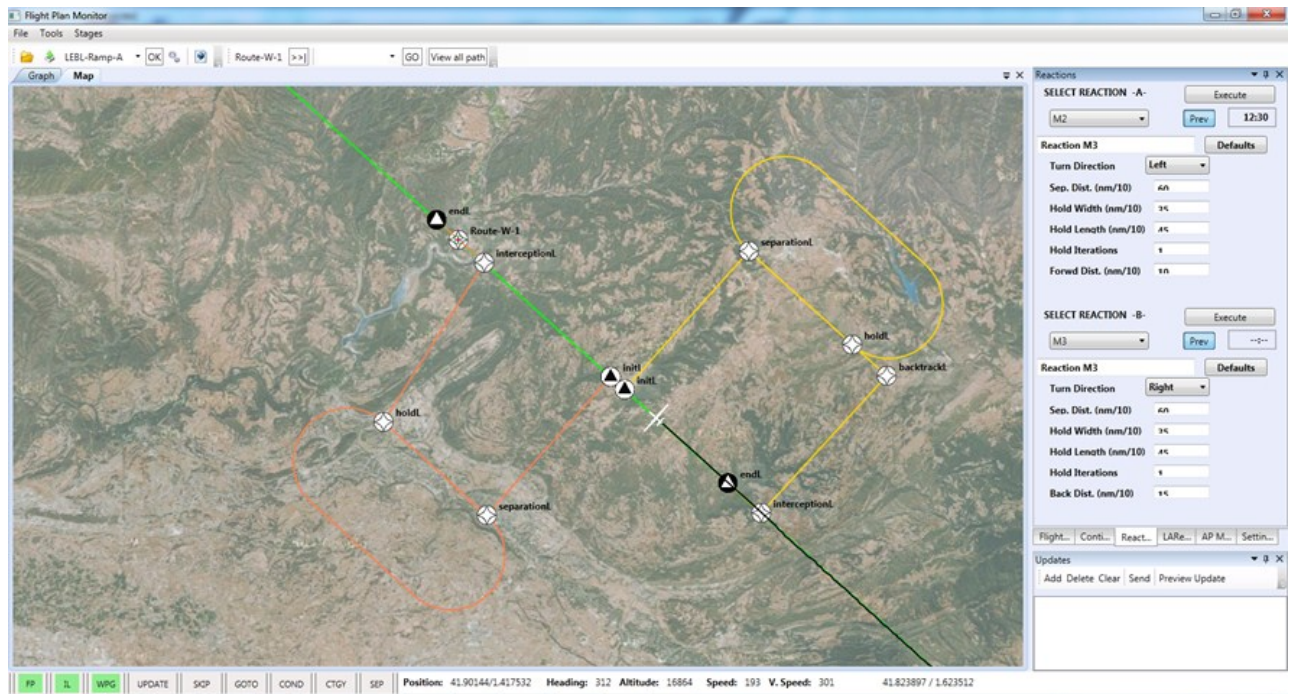


Figure 13: Interface for the manual selection of the separation maneuvers (forward/backward are depicted).

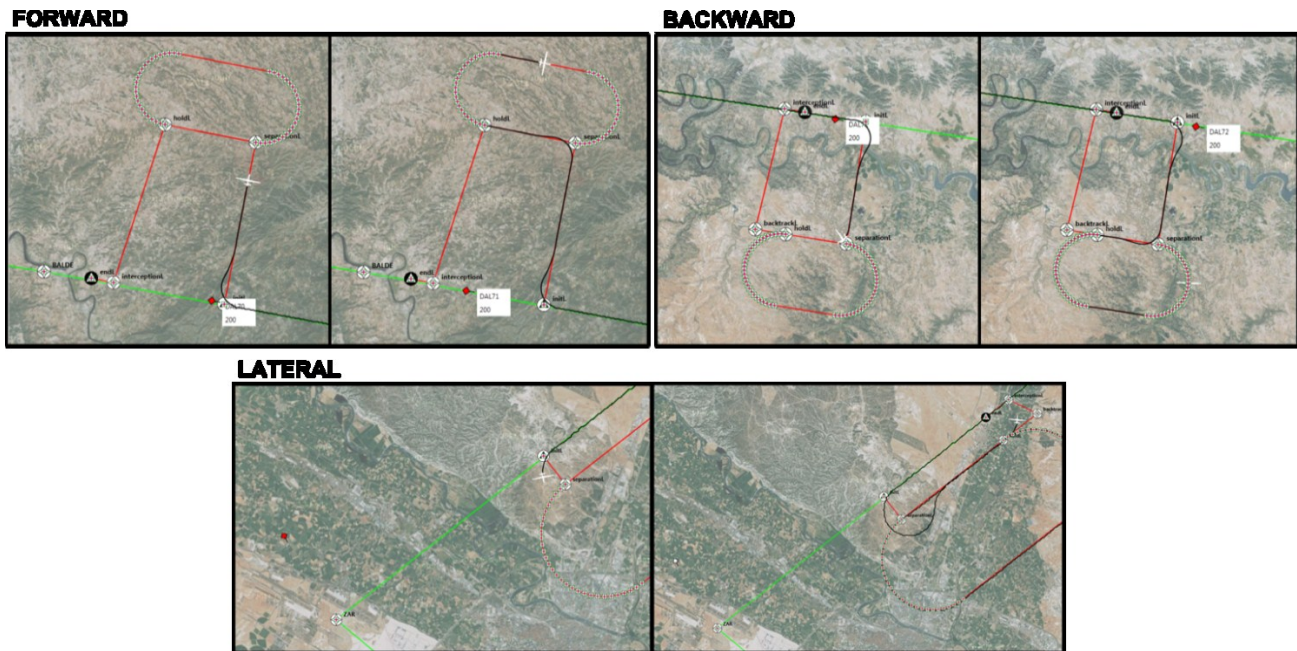


Figure 14: Maneuvering sequences in order to avoid the sequence of conflicting aircraft simulated within eDEP and ISIS.

desired target separation. Finally, for a lateral conflict a holding maneuver is executed designed to avoid proceeding further in the flightplan, thus maintaining separation with DAL1 and DAL2 as seen in Figure 15 (note that DAL0 never becomes a real separation conflict).

Current research includes the development of automated services that will compute the optimum parameters for the separation maneuver once the whole spectrum of UAS/intruder performances have been characterized.

## 6. CONCLUSIONS

This paper introduces a research on the separation conflict scenarios that a UAS may encounter once operating in non-segregated airspace. Conflict geometries and separation maneuvers have been explored for a particular performance instance for both the intruder and the UAS. Our results suggest that specific separation maneuver may

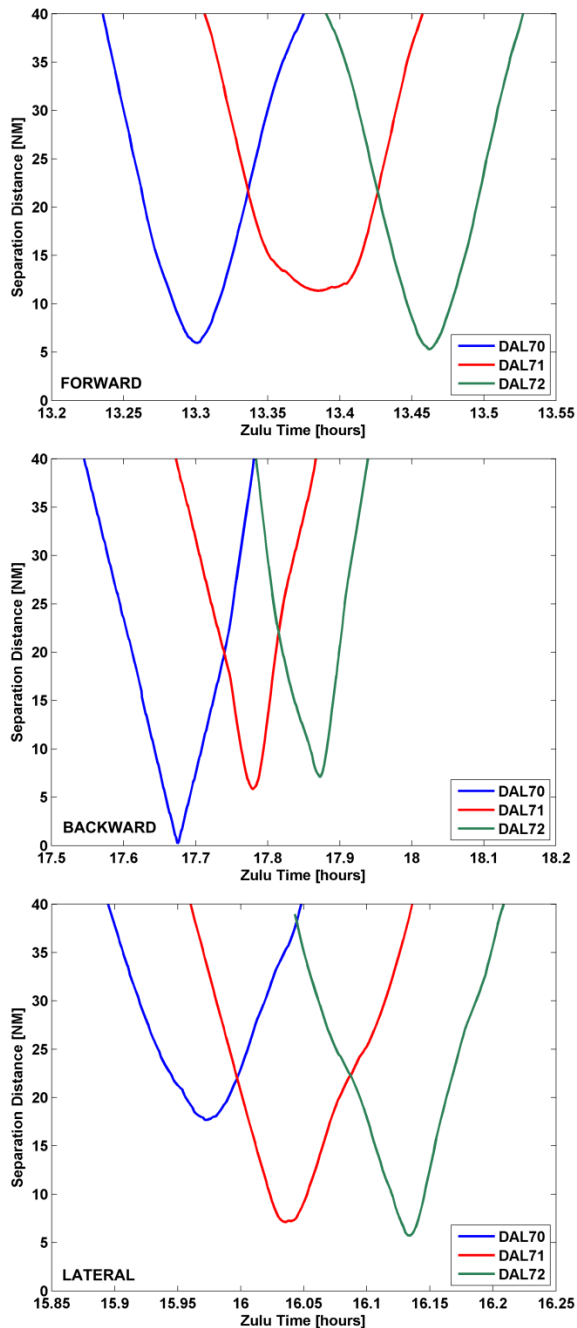


Figure 15: Separation distances as tracked during the combined eDEP-ISIS simulation.

be needed both from the point of view of the limited performance of the UAS and from the negative impact that separation maneuvers may have on the UAS mission.

This work is an initial step towards the analysis of generalized separation conflict geometries. Wider ranges of performances need to be evaluated, but also critical elements that may have a large impact on the separation decision need to be considered like communication latencies, turning limitations when operating at high altitudes, the impact of speed changes, etc. Future work needs to take into account the human factor for both the

pilot and the ATCo, hence realistic simulation scenarios will be created, and both pilot and ATCo confronted to them to evaluate reactions and workload.

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