

# On the design of UAS horizontal separation maneuvers

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**Abstract**—This paper studies the separation maneuvers that an Unmanned Air System (UAS) may execute to avoid breaching the separation safety margins imposed in each type of airspace, namely 3 NM, 5 NM, and 10 NM. The UAS was assumed under the control of its Pilot in Command, with available information about its surrounding traffic through ADS-B or ADS-C, and most likely under the supervision of an ATCo. A number of UAS separation maneuvers have been identified that may guarantee the desired levels of separation if executed with the right parameters and enough anticipation. This paper focuses on identification of the most suitable maneuver for any separation conflict geometry and performance envelop. The conflict geometry is modeled to take into account the speed of both vehicles (the UAS and the intruder), the conflict angle, the turning limitations of the UAS, the reaction time of the pilot, and the communication latency.

## I. INTRODUCTION

The pressure to integrate Unmanned Aerial Systems (UAS) in non-segregated airspace for both military and security/civil missions and applications is steadily increasing both in the EU and USA [1]–[3]. Yet, the lack of a consolidated regulation basis concerning their certification, airworthiness and operations is still mostly banning its utilization beyond conflict theaters. However, it is well recognized that UAS may provide significant benefits among a wide number of applications, being extended surveillance perhaps the most numerous [4], [5].

The nature of surveillance operations themselves introduces a new dimension to the integration problem, as UAS would like to loiter over areas of interest beyond the rigid nature of the airspace where they operate. The UAS performing those surveillance duties 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. Moreover, peculiarities like pilot-UAS communication latencies and, in the worst case, the loss of data-link with the UAS add a final touch of complexity.

This work focuses on the separation maneuvers that UAS may have to execute to comply with the rules of the air, once operating in non-segregated airspace. In aviation, separation assurance and collision avoidance are the two main functionalities employed to minimize the probability of collision between aircraft. 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.

Current standards already enforce to implement 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 [6].

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 (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 [7]. Similar concepts are brought at cockpit level with the Airborne Separation Assurance Systems (ASAS), which aim to delegate separation from controllers to pilots or, at least enhance the pilot's situational awareness [8].

The objective of this work is to model the scenarios where a UAS may enter in conflict with a potentially much faster airplane flying at similar altitudes. All conflicting traffic is assumed to be collaborative; that is, their intentions are known through ADS-B/C or similar services [9]. The conflict geometry should take into account the actual speed of both vehicles (the UAS and the intruder), the conflict angle, the reaction time of the pilot, the communication latency and the performance limitations of the UAS. Poor UAS performance and latency dictates specific requirements in terms of heading changes and minimum reaction times in order to guarantee that the separation between both aircraft is maintained.

Once separation conflicts have been evaluated according to the speeds, angular geometry, and detection ranges, we determined that the classical vector-based separation maneuver may not be sufficient for a wide spectrum of conflict geometries.

Moreover, vector-based maneuvers may have an extremely negative impact on the UAS mission. As a result, a catalog of separation maneuvers has been identified, classifying the most suitable one for each geometry, thus effectively employing a reaction taxonomy. Our objective is to properly evaluate this taxonomy under all reasonable performance envelopes and create an automated advisory mechanism that can benefit both the pilot and the ATCo in order to negotiate the best suited separation maneuver.

The rest of this paper is organized as follows. Section II presents the conflict geometry being studied and describes some of the previous work [10] that analyzed the limitations of typical Medium Altitude Long Endurance (MALE) UAS that entering in conflict with a jet airliner. Section III introduces the prescribed separation maneuvers for each type of separation conflict and the conditions/timing under which they can be safely employed. The conflict geometry is then improved in Section IV taking into account the turning limitations of UAS flying at cruise altitudes and how to take into account the communication latency effects when designing the actual separation maneuver. Finally, Section V concludes the paper and defines future work.

## II. GEOMETRY AND CLASSIFICATION OF SEPARATION CONFLICTS

The most important factors when detecting and solving a separation conflict are the relative angle and the flight performance differences between the conflicting aircraft. With the possible introduction of UAS into civil non-segregated airspace, separation conflicts between UAS and conventional airliners may occur, exhibiting dissimilar conflict geometries. Such geometries need also to take into account the notable differences in flight performance and maneuverability between the UAS and the intruder.

Given a separation conflict, three possible options exist to maintain the required separation and clear the conflict: change the flight level, change the course and/or change the speed. Changing the UAS flight level may not be a feasible solution due to the extremely poor climbing or descending performance of the UAS at typical cruise altitudes. Descend maneuvers may be possible, but will require extremely long cruise-climb to regain the original altitude. Speed changes will be also limited, specially for propeller driven UAS like a Predator-B, while turbofan driven UAS like a Global Hawk may have a wider range of cruise speeds. Similarly, changing the UAS heading will be also limited due to restricted bank angles at cruise altitudes. However, enough separation values can be attained if heading changes are executed well in advance, maintaining altitude and even if the UAS is flying at a speed significantly slower than the intruder.

This section will introduce the basic conflict geometry under evaluation and demonstrate that a typical MALE UAS (a RQ-4 Global Hawk or GA MQ-9 Reaper) can guarantee minimum separation values of 3.0 NM, 5.0 NM and even 10.0 NM, when in conflict with a jet airliner intruder. It will be assumed that both aircraft will remain at the same altitude and that

separation will be guaranteed by changing the heading of the UAS. Once the baseline separation conflict model and maneuvering strategy has been introduced, we will extend it to consider a more realistic situation in which: the UAS cannot turn instantly due to a limited bank angle, its Beyond Line-Of-Sight (BLOS) communications suffering some latency levels, and the UAS pilot needing some time to confirm the separation maneuver.

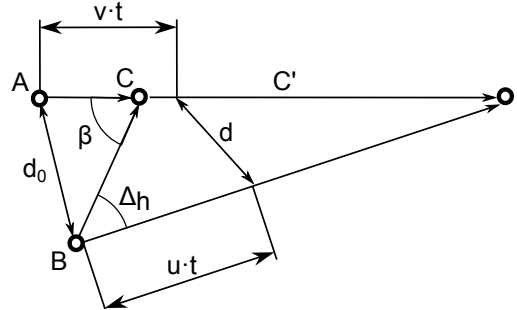


Figure 1. Basic conflict geometry without latency factors or turning limitations.

### A. Conflict geometry and aircraft performance models

Figure 1 describes the simplified conflict geometry used in this section. 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  $C$ ). 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  $\Delta h$ .

The initial position of both aircrafts at points  $A$  and  $B$  is determined by the Time to Conflict ( $t_c$ ). Regardless of other factors like latency,  $t_c$  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  $C$ ).

The performance of the UAS, the speed and turning limitations of each aircraft class (at the considered altitude) have been taken into account. Speeds will range from 300 to 600 kt for the airliner, although an Airbus A320 with cruise speed of 500 kt will be considered in some examples. Speeds from 150 to 300 kt will be considered for the UAS. A Predator-B with cruise speed of 170 kt and a Global Hawk with cruise speed of 300 kt are considered. Figure 2 show the aircraft under consideration.

### B. Conflict classification

In order to properly design the most suitable separation maneuver, conflicts are classified and studied depending on the



Figure 2. Aircraft under consideration.

relative bearing of the intruder aircraft. This strategy allows to identify symmetries between geometries and the peculiarities of each maneuver. Figure 3 depicts the conflict classification selected in our work.

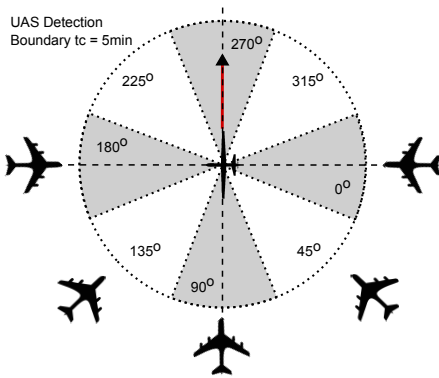


Figure 3. Conflict classification relative to the angle between both aircraft.

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. Figure 4 describes the analysis of the conflict in which the intruder is the Airbus A320 and the UAS is a MQ-9 Reaper on (a) and a RQ-4 on (b). In the  $x$ -axis  $\Delta h$  has been plotted while, in the  $y$ -axis, the minimum absolute distance between both 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.

The analysis shows that, given a  $t_c$  of 5 min for both aircraft, a target separation of 10 NM can be effectively achieved by performing a heading change  $\Delta h \approx 50^\circ$  for the MQ-9 and  $\Delta h \approx 50^\circ$  for the RQ-4  $\Delta h \approx 20^\circ$ .

A backward conflict is 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 5 describes the analysis of the conflict if the UAS is a MQ-9 Reaper on (a) and a RQ-4 on (b). The analysis shows that, given a  $t_c$  of 5 min, a target separation of 10 NM cannot be achieved by the

MQ-9, even if performing a heading change of  $\Delta h \approx 80^\circ$ . Surprisingly, the RQ-4 cannot achieve the separation either, barely reaching the 10 NM limit for a  $\Delta h \approx 55^\circ$ .

Figure 6 deepens the analysis of this scenario by depicting a distance to time analysis. The  $x$ -axis plots the time since the conflict has been detected normalized to  $t_c = 5$  min 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  $90^\circ$ ).

For that particular scenario, it is clear that a slightly longer Time to Conflict ( $t_c = 6$  min) will provide the extra time to reach the 10 NM limit employing similar heading changes that for  $t_c = 5$  min. Alternatively, a separation limit of 5 NM may be targeted in order to maintain the same detection capabilities required to reach a  $t_c = 5$  min.

An oblique conflict is any conflict geometry such that  $\beta \approx 45^\circ$  or  $\beta \approx 135^\circ$  (and the symmetric counterparts  $\beta \approx 315^\circ$  or  $\beta \approx 225^\circ$ ).

Figure 7 shows the resulting scenario for  $\beta \approx 135^\circ$ , in which the UAS turns against or away from the intruder. Turning against the intruder provides enough separation for both the MQ-9 and the RQ-4, while turning against the intruder only provides reasonable separation levels at high speeds; i.e. for the RQ-4. Figure 8 shows the resulting scenario for  $\beta \approx 45^\circ$ . Again, there are large separation differences if turning towards or away from it. In this scenario, almost no separation is gained when turning against the intruder, while turning towards the intruder provides enough separation for both types of aircraft within the 5 min time to conflict.

A lateral conflict is 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.

Figure 9 clearly shows that turning towards the intruder provides valuable separation until heading change of  $\Delta h \approx 60^\circ$  for a MQ-9; much less for a RQ-4. On the other side, turning away from the intruder may simply delay the conflict, and enough separation can only be achieved with turning angles closer to  $\Delta h \approx 80^\circ$ .

### III. CATALOG OF SEPARATION MANEUVERS

Our proposal strictly focuses on separation maneuvers in which the UAS performs the heading change (other scenarios are out of the scope of this paper). A separation minima of 5 NM will be initially targeted based on a time to conflict of 5 min. Although standard separations may also fall in the 3 or 10 NM range, 5 NM is employed as an initial way to define a separation strategy. A time to conflict of 5 min was previously 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 [9]. However, the separation analysis referenced in the prevision section clearly indicates that a slightly longer 7-8 min time to conflict will provide a more comfortable maneuvering scenario for a certain range of

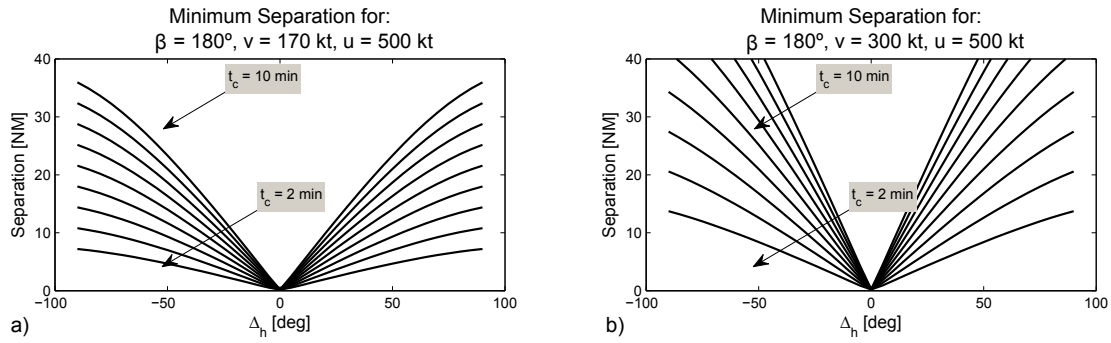


Figure 4. Time to conflict and heading change analysis for a forward conflict.

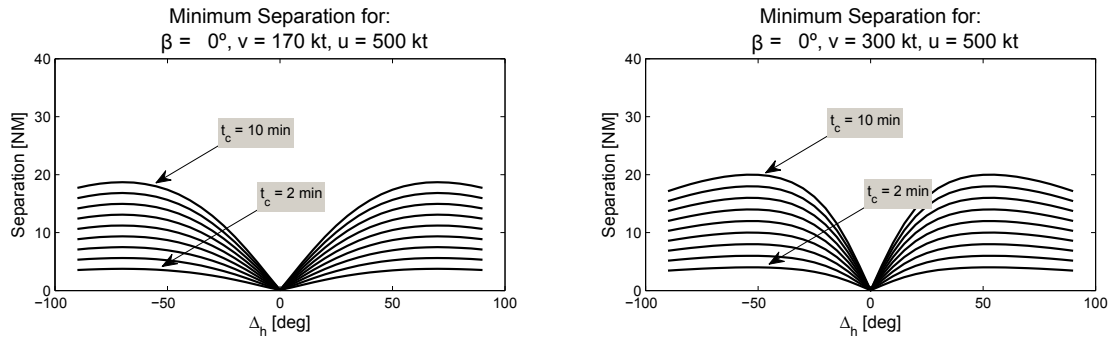


Figure 5. Time to conflict and heading change analysis for a backward conflict.

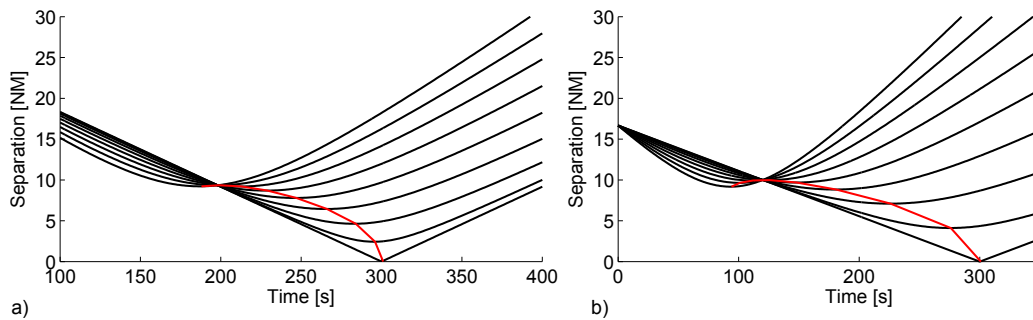


Figure 6. Minimum separation distance according to the heading change for a backward conflict.

low performance UAS if the 10 NM separation limit needs to be achieved.

#### A. Forward and backward separation maneuvers

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, as a maximum heading change is required in order to achieve the desired separation (recall Section II). 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 of  $\Delta h \approx 80^\circ$  to barely achieve a 8-9 NM separation (thus the 5 NM margin is selected to have

an wide margin).

Under these circumstances, for both  $\beta \approx 180^\circ$  and  $\beta \approx 0^\circ$ , Figure 10(a) describes our proposed separation maneuver. An almost maximum turn maneuver is prescribed (although it could be more relaxed in case of a forward conflict) until the UAS reached a position that guarantees the required separation ( $d_{min}$ ). Once the desired separation is reached, the UAS will turn again following its original track or a trajectory just opposite to it. This course if followed 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. 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 as  $\beta \approx 180^\circ$  and  $\beta \approx 0^\circ$ , the separation maneuver needs to be executed either right or left according to the direction that maximizes the separation distance that will

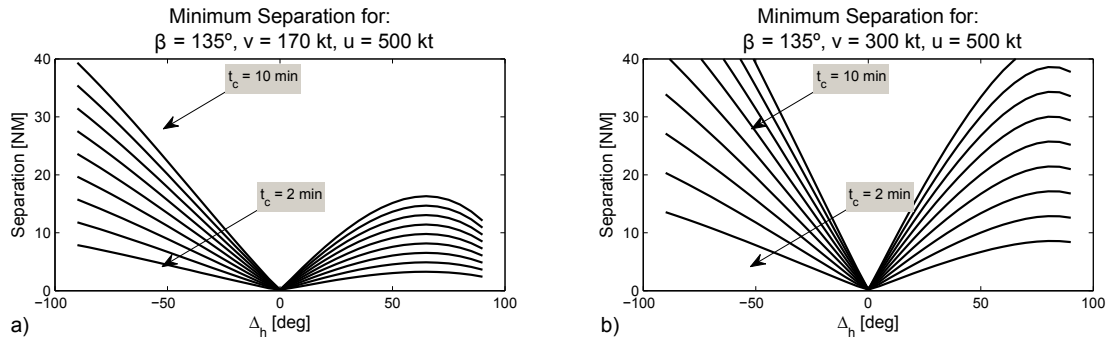


Figure 7. Time to conflict and heading change analysis for an oblique conflict of  $\beta = 135^\circ$ .

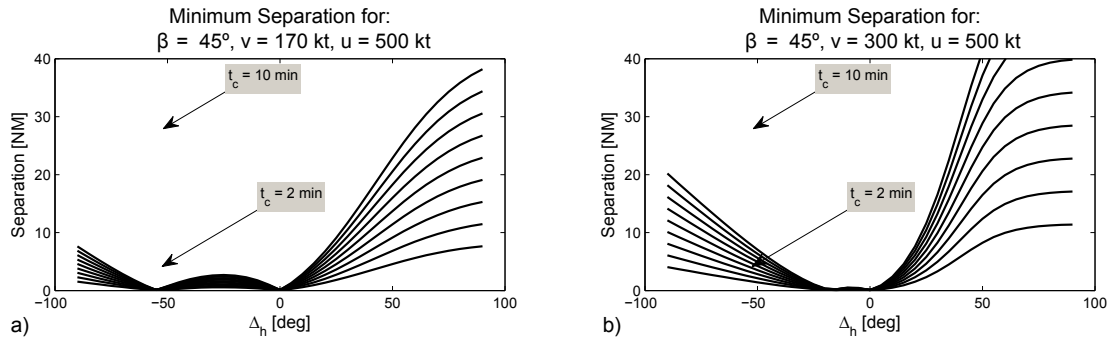


Figure 8. Time to conflict and heading change analysis for an oblique conflict of  $\beta = 45^\circ$ .

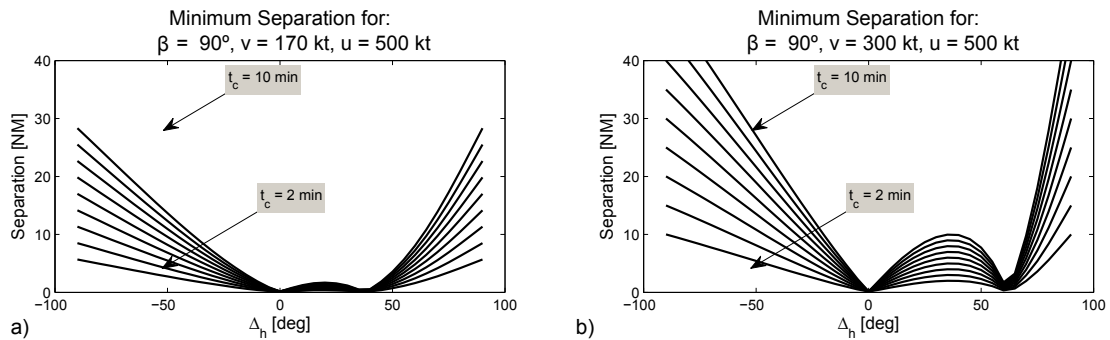


Figure 9. Time to conflict and heading change analysis for a lateral conflict.

be obtained once point  $D$  is reached.

### B. Oblique separation maneuvers

Oblique conflicts do not require a separation maneuver as aggressive as forward/backward conflicts. If the relative angle  $\beta$  is large enough, the UAS may take a trajectory parallel to the conflicting intruder (as seen in Figures 10(b) and (c)). The UAS will turn towards or against 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); but always targeting a given minimum separation value  $d_{min}$ .

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 factors need to be identified in order to identify the best way to employ the maneuver:

- 1) Which range of conflict angles  $\beta$  and Time to Conflicts guarantee a certain level of desired separation.
- 2) How long it will take in order to clear the conflict and return to the original course.

### C. 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

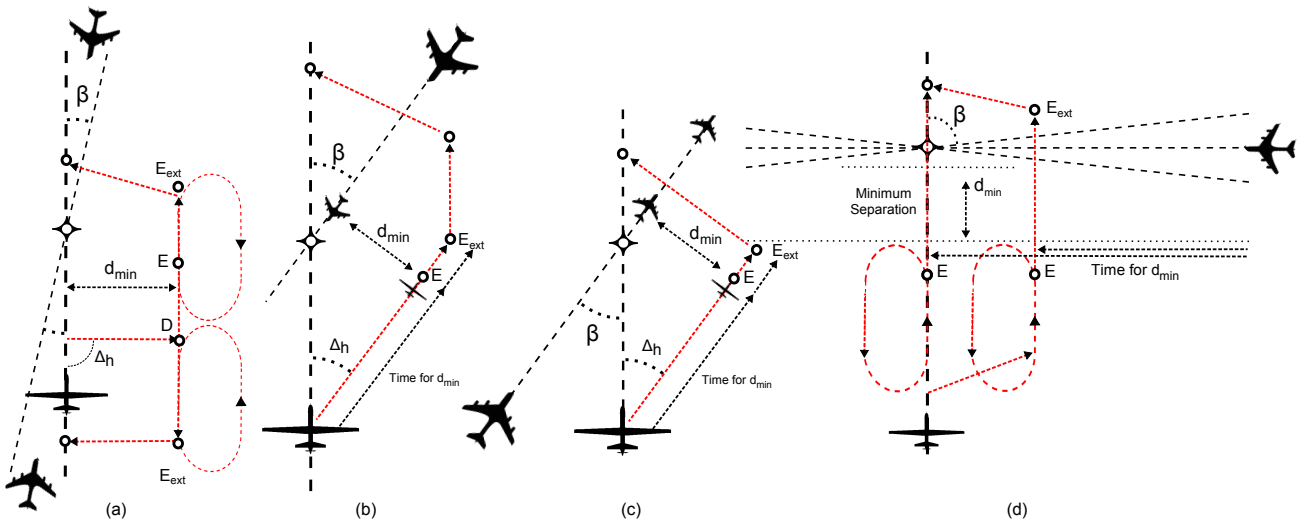


Figure 10. Maximum turn separation maneuver for both forward and backward separation conflicts.

maneuver employed for oblique conflicts requires the UAS to perform a radical heading change that may separate the UAS 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.

Figure 10(d) outlines our proposed strategy for lateral conflicts. The objective is to keep the UAS well-clear of the intruder path, thus a 5 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 stops its forward movement. 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.

#### D. Maneuver selection criteria

The selection of the best suited separation maneuver needs to be assessed for those cases in which the conflict angle  $\beta$  lays in between two geometry regions. The most critical decision is to determine at which point oblique maneuvers are no longer safe (do not guarantee the desired separation limits), and then forward/backward separation maneuvers need to be employed.

The desired separation distance directly depends on the conflict angle  $\beta$  and the selected Time to Conflict  $t_c$ . A bigger  $t_c$  implies that the distance between the UAS and the intruder is larger, but will depend on the speed of the UAS; i.e. the distance traveled in  $t_c$  minutes at the UAS speed. Figure 11

depicts the analysis of minimum separation distance  $d_{min}$  for a 5 NM and a 3 NM objective. Recall that the 10 NM separation objective is unfeasible for a certain range of angles.

The figure clearly indicates that a conflict angle of  $\beta \approx 19^\circ$  is the smaller angle that can be considered for a MQ-9 in order to employ an oblique maneuver to maintain a 5 NM separation distance for forward conflicts. The angle is reduced to  $\beta \approx 13^\circ$  if a 3 NM separation is targeted. The situation theoretically improves for faster vehicles, as the limit is reduced to  $\beta \approx 10^\circ$ , due to the greater distances involved by the  $t_c$  - speed product. The analysis also demonstrated that this geometry is completely symmetrical for backward conflicts. Smaller  $\beta$  angles force using a forward/backward separation maneuver.

Once an oblique maneuver is being selected, it becomes necessary to identify for how long the separation heading needs to be maintained. Here the situation completely changes, detecting extreme differences for oblique conflicts with  $\beta < 90^\circ$  or  $\beta > 90^\circ$  (recall Figures 10(b) and (c)). In the first case, Figure 12(a) demonstrates that the time to reach the minimum distance between UAS an intruder rapidly decreases with the increase of the speed and the turning angle of the UAS (and is always smaller than 5 min). On the contrary, for the second case Figure 12(b) shows that the time to reach  $d_{min}$  increases with the speed and the turning angle of the UAS (and it is quite often greater than 5 min).

In case a forward or backward separation maneuver is required due to the angle limitation factor, a different methodology is required to compute the total time required to clear the avoidance. Here two factors need to be taken into account, the type of conflict (either forward or backward), and the direction to be employed by the UAS to clear the conflict (either keeping its original course or against it). The timing results are completely different for each case and are show in Figure 13. In all cases, the *Separation time* curve indicates the time required by the UAS to separate and gain a 5 NM margin when executing a  $\Delta h \approx 90^\circ$ . After that, the  $d_{min}$  curve indicates

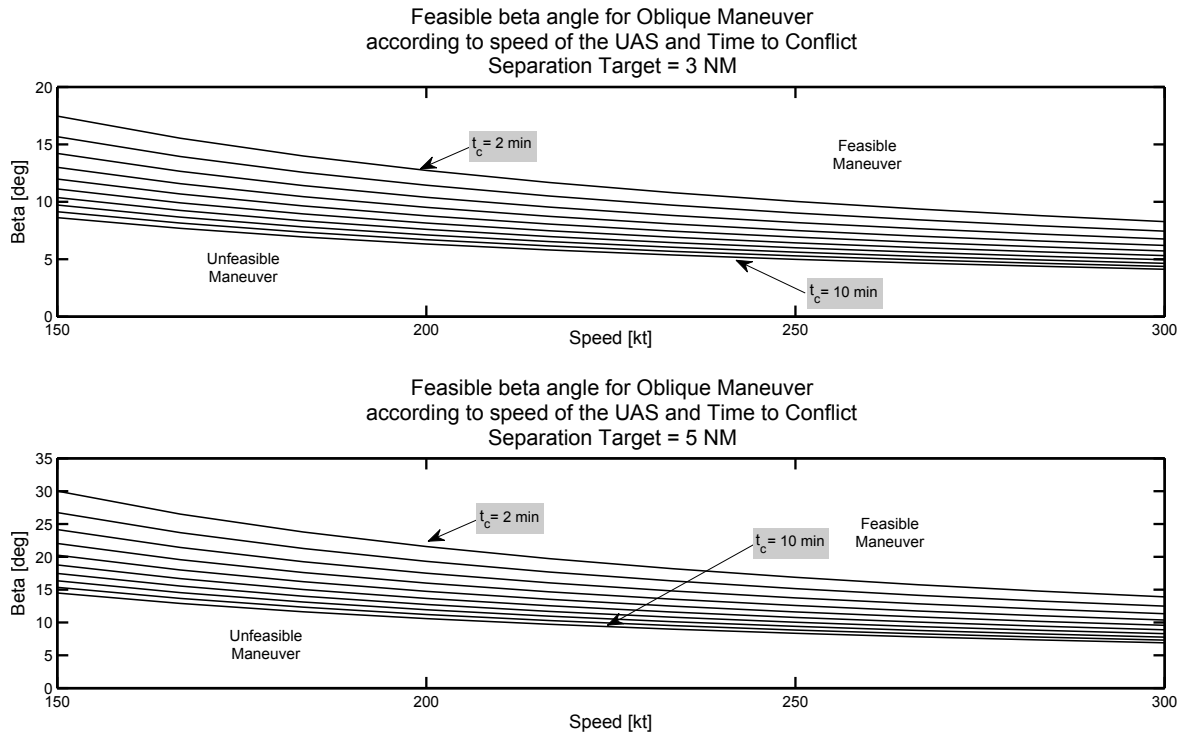


Figure 11. Limiting  $\beta$  angles that define the separation maneuver of choice.

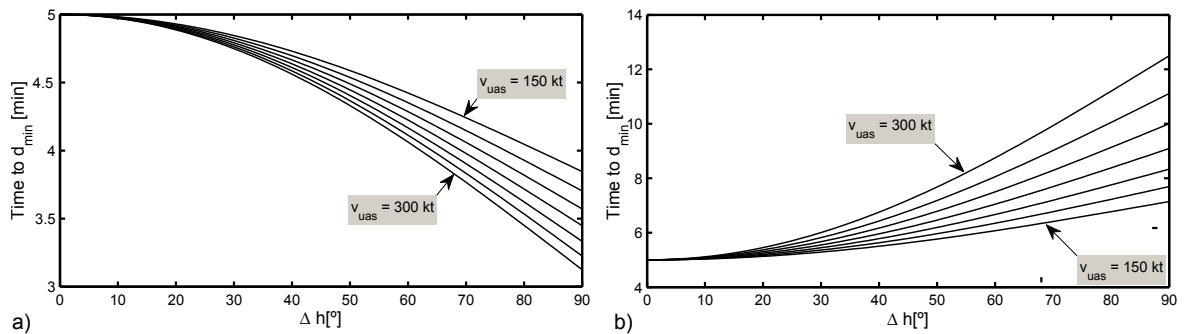


Figure 12. Timing ranges for both forward and backward separation maneuvers.

the time required to reach the minimum separation distance for both aircraft. From there the separation is increased until a further 5 NM are gained (before the UAS turns back to its original trajectory). The time to reach this point is shown in the *Conflict cleanup* curve. The total time is added up in the *Total time to cleanup* curve.

Results show four scenarios that behave completely different from intuition. Maneuvering forward to react to a forward conflict limits to an almost constant value the total time required to clean the conflict. Maneuvering backward produces extremely long maneuvers that need to be avoided if possible. For backward conflicts the scenario changes radically. Maneuvering backwards to clean a conflict reduces to total time to clean the conflict to values well below 3.5 minutes; and maneuvering forward (against intuition) keeps the total maneuvering time to an almost constant value of 5 minutes regardless of the speed of the UAS.

#### IV. IMPACT OF LATENCY AND TURN LIMITATIONS

The initial analysis performed in [10] does not take into account two effects that may have a negative impact in the execution of the separation maneuvers: UAS bank angle limitations and communication latency between the UAS and its pilot. This section will analyze the relevance of its real impact and provide mechanisms to mitigate their effects.

##### A. UAS turn limitations

UAS operating at high altitudes suffer bank angle limitations that restrict the speed at which they can change their heading. This limitation is specially relevant in case the UAS needs to execute an urgent separation maneuver.

Figure 14 depicts a more detailed conflict scenario in which bank angle and roll factors are taken into account. A UAS that predicts a separation conflict with an intruder airliner determines that needs to change its heading and take

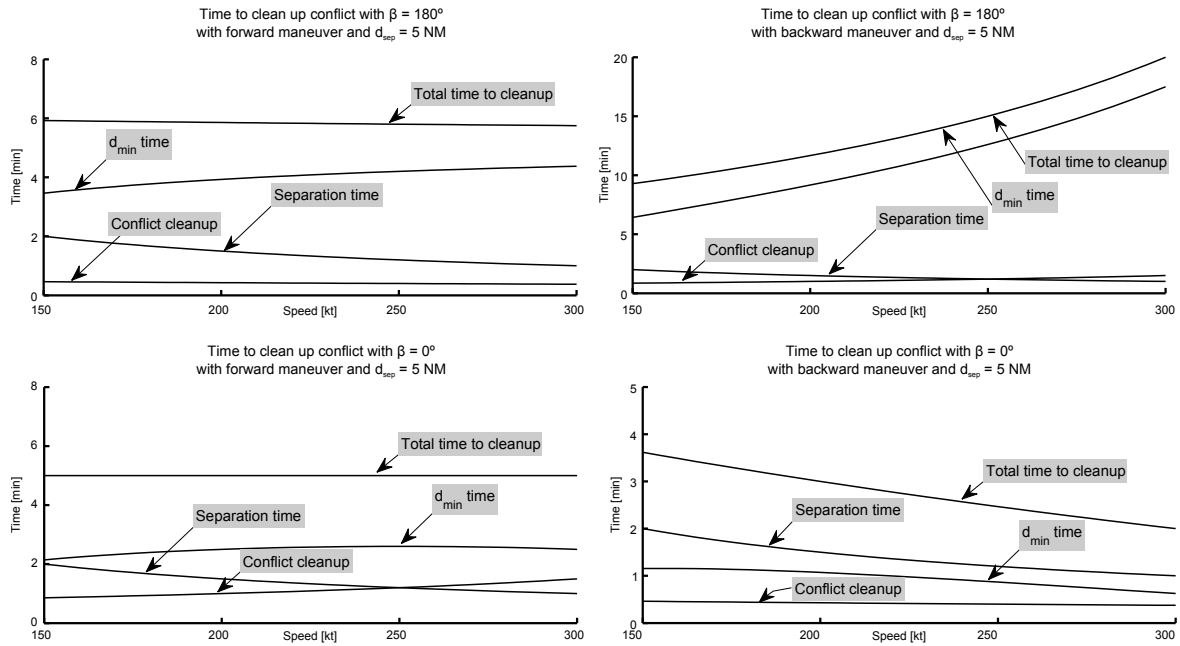


Figure 13. Timing ranges for both forward and backward separation maneuvers.

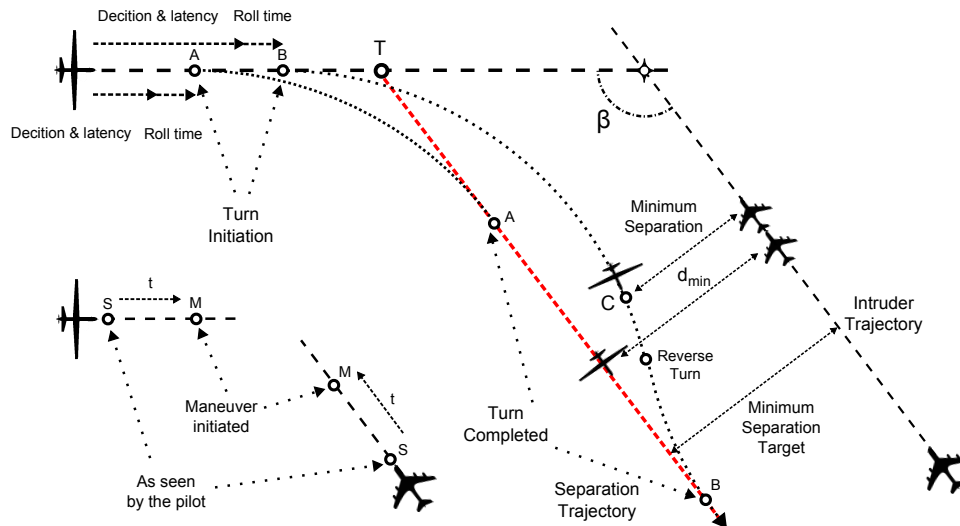


Figure 14. Turn limitation effects affecting UAS separation maneuvers.

a trajectory parallel to the trajectory of the intruder. Both trajectories should guarantee a separation distance well within the selected separation minima (e.g. 5 NM). The separation trajectory under consideration should start at point  $T$ , and it is the trajectory that strictly complies with the separation minima; i.e. and trajectory executed later in time implies a loss of separation. Moreover, it will necessary to determine at which point in space the UAS and the airliner reach their minimum separation, so that the UAS can turn back into its original trajectory or the the next fix in its flight plan. The ability of the UAS to properly intercept the desired separation trajectory is determined by its turning performance and by the turning anticipation used to compensate the actual turning

limitations. Momentarily we will not consider communication latency issues as they will be discussed in the next section.

Once the UAS pilot has committed to the separation maneuver the UAS will initiate its heading change. However, when modeling the turn behavior of the UAS it is well accepted that an initial roll time (that depends on the speed, altitude, etc.) needs to be taken into account before the aircraft actual starts changing its heading significantly. After this initial roll time the UAS will change its heading at the rate determined by its limited bank angle.

Multiple turning scenarios exist depending on the instant in which the UAS initiated its maneuver. Following the trajectory labeled  $A$ , the UAS initiates the maneuver with the



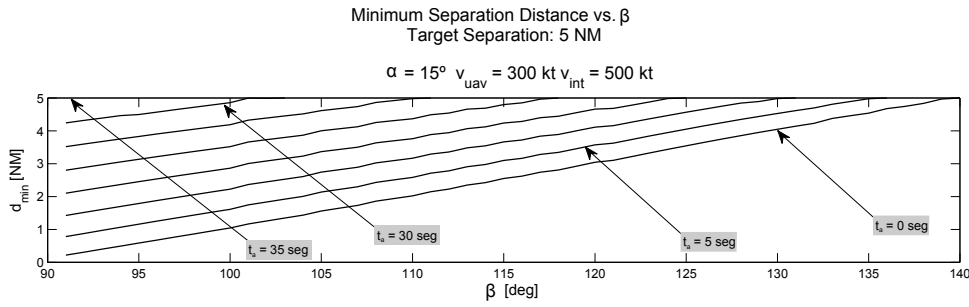


Figure 15.  $d_{min}$  as a function of  $\beta$ .

exact timing that will produce a perfect turn that later on intercepts the separation trajectory at point  $A'$ . From then on the UAS will roll back and follow a straight course until the conflict is cleared. If the UAS performs as described, it will never surpass the separation trajectory thus guaranteeing the minimum separation distance.

On the contrary, if the UAS delays its turn until reaching point  $B$  due to a late decision or its extremely bad turning performance, the UAS will immediately surpass the limits imposed by the separation trajectory. In this situation the UAS will turn right until a point in space in which it will roll back to the left in order to intercept the separation trajectory from the other side at point  $B'$ . During this period of time that UAS has been flying beyond the desired separation target, although it is not clear that separation between the UAS and the intruder has been breached.

The main question to respond is to determine if the point in which both the UAS and the intruder reach their minimum separation distance (point  $C$ ), lays before or after the UAS has been able to intercept back the separation trajectory. Our analysis will limit the number of turning maneuvers to those executed just after surpassing the optimal turning point  $A$  until the theoretical turning point  $T$ . We discuss in detail the scenario in which a RQ-4 Global Hawk performs a separation turn as the impact of the speed on the turn limitations is much important than for a MQ-9 Reaper (170 kt). In fact, results demonstrate that this effect is almost negligible for a MQ-9, but not for a RQ-4.

Figure 15 depicts the minimum separation distance ( $d_{min}$ ) between a UAS flying at  $v_{uav} = 300$  kt and an airliner flying at  $v_{int} = 500$  kt as a function of the conflict angle  $\beta$ . An  $\alpha = 15^\circ$  bank angle has been considered, while the required separation distance has been set to 5 NM. Let  $t_a$  be the time the UAS will start to perform the turning maneuver before arriving to the limit point  $T$ . It can be derived that, if  $t_a > d(A, T)/v_{uav}$ , the UAS will not surpass the separation trajectory (in this case, for a  $t_a > 35$  seg). However, if  $t_a < 35$  seg the minimum separation distance cannot be guaranteed for all range of conflict angles ( $\beta$ ). For instance, if  $t_a = 5$  seg the required separation distance will be infringed for conflict angles from  $\beta = 90^\circ$  up to  $\beta \approx 133^\circ$ . On the other hand, if  $\beta > 133^\circ$ , separation will be guaranteed although separation trajectory will be surpassed.

Let be  $t_{d_{min}}$  the elapsed time since the conflict is detected until conflicting aircraft have reached  $d_{min}$ . Figure 16 plots its evolution as a function of  $\beta$ . Both  $\alpha$ ,  $v_{uav}$ ,  $v_{int}$ , and  $t_c$  are set as in Figure 15. Both blue lines refer to the time until the UAS gets to  $d_{min}$ . The solid line represents the situation when  $t_a = 0$  seg, while the dotted line depicts the case when  $t_a = 15$  seg. Both red lines represent the elapsed time since the conflict is detected until UAS reverses the turn (recall Figure 14), one per each  $t_a$  case. Finally, the green lines represent the elapsed time since the conflict is detected until UAS has reached the separation trajectory. Thus, when the blue dotted line is below the red one, both aircraft reach the minimum separation distance before the UAS reverses the turn. If the blue line is above the red one but below the green line,  $d_{min}$  is reached in the reverse turn phase. Otherwise,  $d_{min}$  is reached when both aircraft are already in a parallel trajectory satisfying the required separation.

### B. UAS-pilot communication latencies

Figure 17 depicts the most common scenarios in which a UAS pilot will have to determine the separation maneuver when trying to maintain its vehicle separated from a potential intruder. Our assumption is that the UAS will receive intention data from cooperative traffic flying within range of their ADS-B or ACAS systems. Conflict detection will be determined on-board the UAS, and the critical information (surrounding traffic and potential conflicts) downloaded to the UAS control station in real time. The data link between the UAS and its control station may be either a LOS link with little or almost no latency, a BLOS link through a satellite network with a non-negligible latency, or a combination of both over time.

The UAS control station may alternatively receive raw traffic information relayed by en-route surveillance services like those provided by ADS-C systems. In that case the conflict detection algorithms will be executed exclusively on the control station.

Once the pilot has the information about traffic and potential conflicts, he may analyze the situation and decide the best suitable maneuver. Decision time will depend on the complexity of the situation and the training of the pilot. This implies that the conflict status may have to be refreshed from time to time, and in general terms every time a batch of ADS-B information

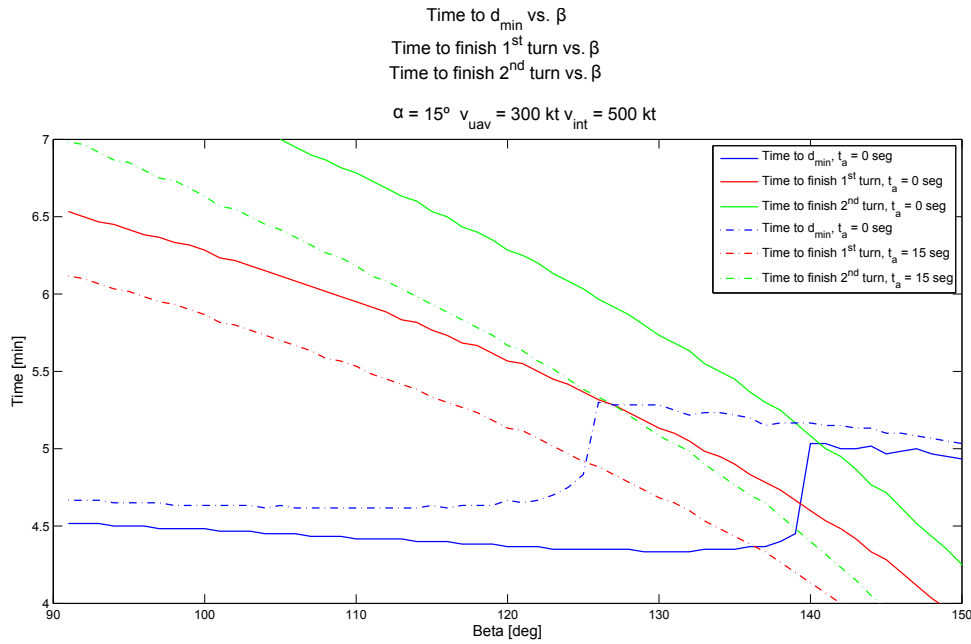


Figure 16.  $t_{d_{min}}$  as a function of  $\beta$ .

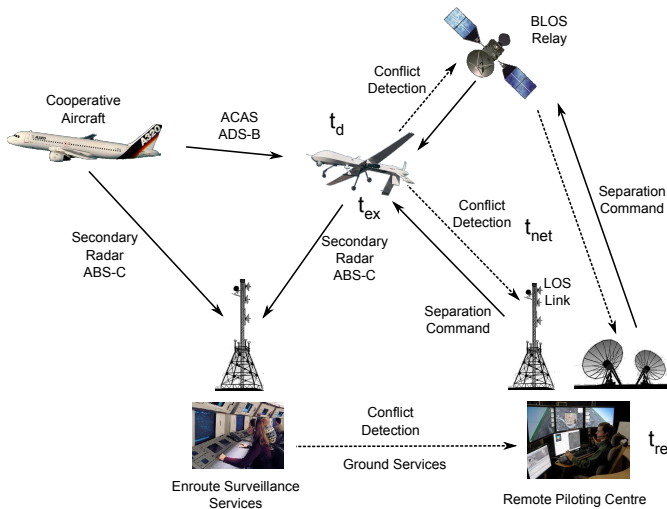


Figure 17. Latency effects affecting UAS separation detection and maneuver commands.

is available for the aircraft in conflict.

After a decision has been taken, the maneuver command will be relayed to the UAS either through the LOS or BLOS command and control link available at that time. Only then the UAS will actually start to execute the required separation maneuver.

Overall, it is clear that there exists a non-negligible time lapse from the instant an incoming ADS-B message is received at the UAS to the time a potential maneuver is executed by it in response. The total time lapse is composed of the following components:

- $t_d$  Time to run the conflict detection algorithms on-board the UAS and prepare the conflict message to be sent to

the control station.

- $t_{net}$  Air to ground network time, that may strongly vary depending on the type of link being used: LOS or BLOS.
- $t_{re}$  Reaction time of the pilot, assuming that the time to show the conflict on the screen is negligible.
- $t_{net}$  Ground to air network time, that will vary depending on the link, but that locally will be almost equivalent to the time to download the conflict message.
- $t_{ex}$  Time required by the UAS to start executing the separation maneuver.

Eliminating the pilot's decision time from the equation, the rest of latency factors can be effectively bounded. Both  $t_d$  and  $t_{ex}$  fully depend on the computation capacity on-board the UAS, and should be quantified once specific avionics is selected. Overall, less than 500 ms per task can be assumed. Network time will move from a few milliseconds if a Line-Of-Sight (LOS) link is used, to 1-2 seconds if a BLOS satellite network is employed. Key to this reasoning is the fact that, at a given instant of time, it will be perfectly known which type of network is being used. Moreover, the air-ground-air total latency can also be quantified by using round trip *ping* messages (quite common on ground networks).

Once the total latency (except the pilot factor) has been identified, any tool supporting the executing of separation maneuvers should take into account this factor. Given that both the UAS and the intruder positions are obtained on the air, from that point in time to the instant in which the maneuver command is executed, both vehicles will have traveled the corresponding distance according to their individual speed, heading and latency bound. The main impact of all this process is that when the UAS pilot analyzes a conflict scenario and decides a maneuver, he has to take into account the predicted

position of both vehicle once the maneuver command reaches the UAS. As seen in Figure 14, the overall latency factors imply that any separation analysis must be performed taking the predicted locations of both aircraft. If this is properly implemented, the latency factor can be removed from any further analysis.

## V. CONCLUSIONS AND FUTURE WORK

This paper has deepened the investigation on a number of separation strategies that may help the integration of UAS in non-segregated airspace. Even though collision avoidance is a key factor to operate in shared airspace, it remains a last resort layer while separation management should be the most used strategy that guarantees the safety of operation. Thus, separation maneuvers have been analyzed by assuming that, either ground or air -based surveillance technology will be available to provide a reasonable conflict detection range.

In order to define a concept of operation to be employed by both ATC and pilots, the limiting factors of each conflict geometry has been studied for a range of realistic UAS. Geometries have been classified showing that classical open instructions based on vectoring may not be efficient and even sufficient to resolve some conflict scenarios. Separation maneuvers are proposed and analyzed by taking into account speed, angles, turn limitation factors, etc. Moreover, the required duration of each separation maneuver has been also determined, indicating the level of optimality of the separation strategy by the separation level being achieved, but also by the reduction of the overall time in which the UAS needs to diverge from its planned trajectory. This analysis finally provides the full picture and will permit to create a sound strategy to select the best separation maneuver to resolve all potential conflict scenarios.

Future work will fully automate the decision process for a realistic range of aircraft performances. How to benefit from a limited range of speed changes will be also incorporated into the model.

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## REFERENCES

- [1] P. Ostwald and W. Hershey, "Helping global hawk fly with the rest of us," in *ICNS Conference*, 2007.
- [2] M. Gillian, G. J., and V. Cox, "Integration of unmanned aircraft systems into the national airspace system. concept of operations v2.0," American Society of Testing & Materials, Tech. Rep., Sep 2012.
- [3] H. H. Hesselink and D. R. Schmitt, "Uas air traffic insertion starts now," National Aerospace Laboratory NLR, Tech. Rep., 2011.
- [4] S. Tenoort, "Concept for civil uas applications," INOUI: Innovative Operational UAS Integration, Tech. Rep., May 2008, tech. Rep. D1.2.,
- [5] UAVNET, "European civil unmanned air vehicle roadmap, volumes 1 and 2," Available on-line at: <http://www.uavnet.com>, 2005.
- [6] P. Brooker, "Air traffic control separation minima: Part 1 the current stasis," *Journal of navigation*, vol. 64, pp. 449–465, 2011.
- [7] 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.
- [8] —, "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>.
- [9] 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.
- [10] M. Perez-Battle, E. Pastor, and X. Prats, "Evaluation of separation strategies for unmanned aerial systems," in *Proceedings of the 5th International Congress on Research in Air Transportation (ICRAT)*. Berkeley, California (USA): EUROCONTROL / FAA, May 2012.