DELEGATION OF SEPARATION ASSURANCE TO AIRCRAFT: TOWARDS A FRAMEWORK FOR ANALYSING THE DIFFERENT CONCEPTS AND UNDERLYING PRINCIPLES

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Abstract

A wide range of studies has been carried out so far in the domain of delegation of separation assurance to aircraft, leading to various concepts, applications and techniques. The present article is an attempt to provide a framework for analysing these studies from an operational perspective to a more theoretical point of view. The framework is based upon a new dimension – the notion of "level of delegation". The article addresses the operational aspects, the cockpit aspects through the notion of "level of assistance" and the system point of view through intent, resolution and co-ordination characterisation.

1 Introduction

The major challenge facing Air Traffic Control (ATC) is to enhance air traffic capacity and flight efficiency while providing safety improvements. However, the forecasted traffic density growth in Europe and in the United States over the next fifteen years suggests that solely improving ground systems might not be sufficient to achieve the required capacity at appropriate safety levels. The development of a close co-operation between ground and airborne sides might be required to achieve this challenge, and the delegation of separation assurance from controllers to pilots is one promising option of co-operation. It takes advantage of emerging CNS/ATM technologies in pre-operational state – ADS-B or TIS-B [34] – along with additional avionics such as a Cockpit Display of Traffic Information (CDTI) providing the pilot with a picture of surrounding traffic [35].

A wide range of studies has been carried out so far in the domain of delegation of separation assurance to aircraft, leading to various concepts, applications and techniques. Therefore, a general framework for analysing and linking the different studies from an operational perspective to a more theoretical point of view, is of interest.

From an operational point of view, a classification of different applications has been proposed, based upon airspace type and phase of flight [34]. A complementary taxonomy has been proposed based on three generic classes of application – traffic situation awareness, tactical co-operation and strategic co-operation [13]. In [30], the different techniques for conflict detection and resolution are classified, based upon several system characteristics, such as the conflict criterion used. In addition, the consideration of the possible modes of human machine co-operation in ATC has led to the notion of level of automation [15][32].

The present article is an attempt to provide a framework for analysing the different studies in the domain of delegation of separation assurance to aircraft. It is based upon a proposed new dimension – the notion of "level of delegation". The article is organised as follows: section 2 addresses the operational aspects and introduces the notion of level of delegation. Section 3 discusses the cockpit aspects through the notion of "level of assistance". Finally, section 4 addresses the system point of view through intent, resolution and co-ordination characterisation.

2 Operational perspective – Levels of delegation

The applications can be classified upon airspace type and phase of flight as in [34]. For example, considering the type of airspace a simplified (non exhaustive) list of applications can be structured as follows:

- Oceanic: in-trail climb or descent, overtaking.
- En-route: in-trail climb or descent, crossing, overtaking.
- Terminal area: longitudinal station keeping, traffic merging.
- Approach: longitudinal station keeping, closely spaced parallel approach.
- Airport: runway incursion, surface movement and guidance.

A more generic classification has been proposed in [13] based upon three classes of application:

- Traffic situation awareness: to enhance pilot traffic situational awareness by providing information on the environment through a CDTI.
- Tactical co-operation: to help in managing relative movement between two proximate aircraft. This can be divided into two sub-classes: distancing applications such as the ASAS crossing procedure [6] and shadowing application such as station keeping or closely spaced parallel approaches.
- Strategic co-operation: to help the pilot in managing his own route with agreement of other aircraft and ATC over a long time horizon. Autonomous aircraft under free-flight conditions is a typical example.

A potential way to further refine this last taxonomy is to introduce the notion of "level of delegation" as reused in [19]. It provides insight of the different applications to support the analysis the concept of delegation. Considering the general task of separation assurance from either human or system point of view, three high level tasks can be identified:

- Identification of problems, mainly detecting potential losses of separation (conflicts) between aircraft.
- Identification of a solution when a problem has been detected, typically identifying which aircraft has to manoeuvre and the type of manoeuvre to be executed, *e.g.* a left turn.
- Implementation of the solution, *e.g.* selection and activation of the appropriate heading changes, and monitoring of the implementation.

Following this high level description, three major levels of delegation can be identified:

- Limited delegation. The controller is in charge of both problem and solution identifications. Only implementation of solutions and monitoring are delegated to the pilot.
- Extended delegation. The controller is in charge of the identification of problems, and delegate to the pilot the identification and implementation of the solution, and the monitoring.
- Full delegation. Pilots are responsible for all the tasks related to separation assurance: identification of problems and solutions, implementation and monitoring.

2.1 Limited delegation

The visual crossing report clearance is a typical case of limited delegation: the encounter between two aircraft is identified and announced by the controller. The pilot is in charge of reporting when he estimates visually that the crossing is completed and possibly of resuming his flight plan. A list of other possible applications of limited delegation has been proposed through RTCA [34][40] for instance station keeping, in-trail climb and descent. Information required on traffic is initially limited to flight state (position and velocity), along with a CDTI indicating velocity and closure rate of a target aircraft. For station keeping, an initial task scheduling has been proposed [40].

The concept presented in [21] introduces the concept of "flexible use of delegation" by providing the possibility to use different sub-levels of limited delegation. Two classes of application are envisaged: crossing and passing in en-route, and sequencing in terminal areas. For crossing and passing applications, the sub-levels are:

- Identification of the "clear of target". The controller provides the separation by issuing the appropriate clearance. The pilot has to identify and report the "clear of target". The controller is then expected to authorise resume climb or normal navigation.
- Resume climb or normal navigation. Again, the controller provides the separation by issuing the appropriate initial clearance. The pilot has to (1) report "clear of target", and (2) resume climb or normal navigation.
- Implementation of manoeuvre. The controller selects the type of manoeuvre to provide separation. The pilot has to (1) work out and execute the appropriate value for this type of manoeuvre, (2) report "clear of target", and (3) resume climb or normal navigation.

The task delegated to the pilot can thus range from monitoring up to implementation. For each problem, the controller has the ability and responsibility to select the appropriate level of delegation depending on various factors such as traffic conditions, airspace constraints, and his practice level. An initial evaluation indicates that this approach is felt "promising" by controllers, and should increase their availability [39].

2.2 Extended delegation

The extended delegation can occur in visual clearances. Although the encounter between two aircraft is identified and announced by the controller, the pilot can be in charge of altering his flight path to visually stay apart the designated traffic. A similar case happens in the approach phase, when the controller asks the pilot to visually stay apart from a lead aircraft. The "ASAS crossing procedure" proposed by CENA can be seen as another case of extended delegation, using a CDTI with in addition relative track information [4][6]. This application is intended to be used in an en-route and managed airspace. First the controller identifies a conflict, then he selects the manoeuvring aircraft and lets the pilot decide which solution to use. The delegation thus relies on controller initiative and uses a specific phraseology to communicate the instructions of delegation.

2.3 Full delegation

All the "autonomous aircraft", "self separation" and "free-flight" applications fall in the context of full delegation [7][9][10][26][36]. This type of application is mainly intended to be applied in en-route airspace. Two types of organisation are targeted: either managed airspace with mixed equipage (i.e. equipped and non equipped aircraft) [9][36], or dedicated airspace with all aircraft equipped [10] such as the Free Flight Airspace proposed in [18].

In the context of dedicated airspace, the role of the controller would dramatically change from traffic control to service regulatory, search and rescue, and possibly to flow management. In the context of managed airspace, the role of the controller would consist in providing separation for non-equipped aircraft while letting equipped aircraft self separating [9][36]. To reduce the possible interactions between equipped and non equipped aircraft, some "filters" can be added such as segregating aircraft by flight level or using protected airways for non-equipped aircraft [36]. These filters can also be considered as transition paths towards free-flight. In both organisations, the controller could also have the task to intervene on equipped aircraft to handle non nominal cases, such as when a conflict is not solved in due time (principle of "ATC by exception"). Is such cases, the controller is moved from an "anticipative" behaviour to a "reactive" one, thus raising the question of a possible loss of situation awareness and possible increase of mental workload, as highlighted in [9][14]. Some experiments indicate that in a context of mixed equipages, the uncertainty about intent of equipped aircraft induces additional workload [9], and other experiments conducted with military controllers tried to compare situations with intent versus without intent [20]. It was also suggested that the operational background and the working practices of military controllers could be more appropriate for free flight scenario than their civilian counterparts [20].

2.4 Discussion

Beyond the applications presented, the main issue arising in the context of the delegation in managed airspace is linked to the direct and side effects of the delegation that must be anticipated and mentally integrated by the controller. Indeed, the delegation is:

- Temporally limited, and the controller has to recover full management of separation assurance. (Specific to extended and limited delegation.)

and/or

- Spatially delimited, and the impact of trajectory modifications on non delegated or non equipped aircraft must be avoided. (Valid for all levels of delegation, full delegation in managed airspace included.)

However, the level of delegation may have a strong impact on (1) the predictability of pilot's possible future actions and trajectories, and (2) on the availability and situation awareness of the controller. Indeed, on one hand, a very limited delegation would maintain a high level of predictability of aircraft behaviours and trajectories from controller's point of view, with a counter part of limited gain in controller workload. On the other hand, a more extended delegation leaves more autonomy for the pilot to manage the solution, with a risk of a possible reduction of predictability for the controller. This should be considered carefully since at some extend, a "significant" loss (*e.g.* inability to anticipate any future actions and trajectories) would probably dramatically decrease the availability and the situation awareness of the controller ("mental picture" spoiled). As a side effect, the availability of the airspace occupancy would also decrease, and no gain in capacity, efficiency or safety could be expected. The potential risks and consequences of loss of mental picture are confirmed in [9]. Therefore, the level of delegation used appears to be a critical factor. Since the appropriate level of delegation strongly depend on traffic conditions, airspace constraints, and on the practice level of each controller, identifying and setting it in advance to its optimal level is thus not an option. The notion of "trade-off in human factor solutions" as introduced for ATC in general in [32] but is also valid for the delegation of separation assurance to aircraft. Hence, the selection of the delegation level should lead to reach such a trade-off.

3 Cockpit perspective – Levels of assistance

Following the applications mentioned before, various on-board assistance schemes have been proposed. Similarly, a possible way to classify and characterise these schemes is to consider the "level of assistance" provided. Six major levels of assistance have been identified [22].

Actual: presents the situation based on current flight parameters of subject aircraft. It may include some predictive features, typically for displaying the point of loss of separation or the point of closest approach. The display proposed in [6] to support the "ASAS crossing procedure" is a typical example based on flight state information: the situation with respect to the target aircraft is presented through a relative speed line and a 8Nm circle centred on the subject aircraft position. A set of displays using different levels of intent information (flight state, commanded values and trajectory) to indicate conflict bands is proposed in [2].

What-if: provides the capability to test potential manoeuvres. Typically, [26][27] has defined a predictive tool to assess a risk of conflict, which uses target values selected on the autopilot. The effect of potential changes of heading and/or speed can thus be tested before they are engaged. For an trajectory based approach, [10] provides a graphic editing capability for the subject aircraft trajectory which is used in conjunction with "no-go" zones generated by both conflicting and surrounding aircraft. A new working trajectory can thus be edited and tested before becoming active.

Red/green range: indicates the range of authorised and forbidden manoeuvres. The example is ACAS (Regardless that ACAS is designed for collision avoidance, and not for separation assurance) which provides red and green arcs on the vertical speed indicator. (For heading or bank angle with the former TCASIII, similar principles were envisaged.)

Scale of separations: indicates the separation value for a range of possible manoeuvres, typically for heading or speed changes. This allows the pilot to identify in advance, i.e. with no prior manipulation, the manoeuvre to be performed. A set of displays for different types of applications (mainly crossing and station keeping) has been proposed in [22].

Advisory: indicates the manoeuvre to be performed. Again, ACAS is a typical example of a system providing advisories, as well as the system proposed in [36]. The pilot has to follow exactly the manoeuvre computed to solve the conflict (or to avoid the collision for ACAS). The solution trajectory automatically generated in [10] can also be seen as an advisory. In that case however, the pilot can ask for other solution trajectories by giving high level directives, e.g. pass to the left.

Automatic: computes and executes the action.

As stressed in [33], the on-board assistance scheme required is closely linked to the underlying operational concept and related procedures, *e.g.* what tasks are intended to be delegated to the pilot, and how? For instance, the extended delegation requires less assistance on board than the full delegation since conflict detection is performed by the controller.

The "actual" level of assistance should be sufficient for a monitoring task, whereas a "what-if" should be the minimum level of assistance for implementing a manoeuvre. However, finding the appropriate manoeuvre with a "what-if" requires varying one (and possibly more) flight parameter. The "advisory" level could provide further assistance, but it should not be used alone. Indeed, it does not provide elements for the understanding of the situation, and thus imposes to rely upon automation [26]. In addition, no real interaction with the pilot can naturally take place. Finally, a strong limitation of the existing "advisory" based systems (at least ACAS and [36]) relies on two points. First, the assistance scheme is switched-off when the "clear of traffic" is issued. Second, the "clear of traffic" only depends on proximity conditions typically when closest point of approach is passed, without any considerations on where and how the pilot will resume his trajectory. Whereas this is acceptable and somewhere consistent for collision avoidance, this may be highly critical for assuring separation in medium and low converging encounters: nothing prevents the pilot from getting back into conflict. (In other words, the notion of "clear of traffic" is not absolute, but is relative to a trajectory.) To deal with this issue, some preventive indications could be introduced after "clear of traffic". Instead, a "what-if" naturally provides a simple way to do it: the "resume" manoeuvre can be tested before it is actually engaged. Considering the possible limitations of the "what-if" on one side (multiple testing), and the "advisory" on the other (mainly automation dependency), the "scale of separations" is an intermediate assistance level, that can be seen as an extension of the binary "red/green ranges" towards an "analog" representation of the effect of different manoeuvres. In addition, it could remain valid and meaningful even after "clear of traffic".

4 System perspective

The underlying theoretical principles mainly deal with conflict detection and resolution issues [30], will be presented and analysed under the following key points:

- The level of surveillance information, that can range among "flight state", i.e. position and velocity of aircraft, to "full intent information" based on aircraft trajectories.
- The resolution strategy, typically "reactive", i.e. producing flight state only, or "planning", including all variants of planning – centralised, distributed, or prioritised.
- The co-ordination strategy among aircraft, typically "simultaneous", i.e. all aircraft involved solve the problem simultaneously, or "sequential", i.e. the aircraft solve the problem according to a sequence order.
- The set of aircraft considered for co-ordination, which can range from "pairwise", *i.e.* co-ordination between the two aircraft immediately in conflict, to "multiple", *i.e.* co-ordination among a "cluster" of aircraft that are directly and indirectly in conflict.

4.1 Level of surveillance information

The issue is the level of information required from other aircraft to ensure the task delegated to the pilot, which can range up to full conflict detection and resolution. As a consequence, what level of information on own aircraft must be provided to other aircraft?

The level of information on other traffic can range among:

- flight state, i.e. position and velocity,
- basic intent based on the target values selected on the autopilot,
- full intent based on the trajectory generated by the FMS.

The level of information should have a strong influence on different elements, mainly:

- The theoretical capability to identify conflict situations with an appropriate trade-off between false alarms and missed alarms (i.e. lowest false alarms with lowest missed alarms) [37]. For example, in a route structured environment, conflict detection based only on flight states would lead to a too high false alarm rate if the look-ahead is above 60s [5].
- The theoretical capability to identify solution manoeuvres taking into account aircraft objectives beyond collision avoidance. For example, in a low converging encounter, intent information is needed to elucidate whether aircraft should aim at having parallel or crossing paths.
- The human factor issues such as the ability to understand the situation. Potential benefits of using intent information in crossing scenarios has been identified in [2][31]. In addition, similar indications using intent and "implicit" information (e.g. expected speed reduction indicated on charts) were obtained for station keeping and traffic merging [33].
- The overall stability of the traffic: how does it react from a system point of view with conflict detection and resolution based on flight state with increasing density? Or, considering a given level of information and traffic density, with different look-ahead horizons?

4.2 Resolution strategy

Two main principles for resolution strategy can be identified:

Reactive resolution that gets periodical updates of the situation as input, typically through flight state, and only produces tactical manoeuvres as output, as opposed to strategic manoeuvres such as FMS trajectory modifications. A reactive resolution can also produce some "intent" information (e.g. by defining the next TCP at the closest point of approach) but due to periodic computation and update, it will have to be periodically updated. The intrinsic short term validity – thus, its usable time horizon – of this information is similar to the flight state update rate.

The ACAS logic is a typical example of reactive mechanism (for collision avoidance), but limited to pairwise situations. The force field techniques is another example that can be used to ensure multiple aircraft encounters [12][28][38]. The principle of reactive resolution leaves free the number of involved aircraft that should/must manoeuvre. Typically, the ACAS logic does not require that in a case of ACAS/ACAS encounter, the two aircraft moves. However, field force logic are usually used in conjunction with simultaneous movements, which imposes some form of real-time co-ordination between manoeuvres.

Planning resolution that typically get trajectories as input (but could work with flight state), and is capable to produce a trajectory. Different planning techniques exist:

- Centralised: one "agent" (ground or airborne) plans a trajectory for each mobiles involved. Different techniques exist, such as optimisation technique [11][25].
- Distributed: each mobile involved plans its new trajectory at the same time while ensuring overall consistency with other. This is investigated in the field of distributed artificial intelligence and multi-agent systems [24][29].
- Prioritised planning: each mobile plans its new trajectory according to a priority order [1][10]. The prioritised planning has been introduced in Robotics [16] to reduce computational complexity of motion planning for multiple mobiles. The underlying idea of this technique is to turn a problem of motion planning for multiple mobiles, into a sequence of motion planning for one mobile among moving obstacles. In addition to the use of a priority order, classical techniques can be used, such as geometric construction [23], force field plus post-processing [3].

4.3 Co-ordination strategy

Two different ways for co-ordination can be identified:

Simultaneous: the aircraft solve the problem simultaneously. With a reactive resolution, i.e. when aircraft move simultaneously, the key point relies on the capability to ensure a real-time co-ordination of manoeuvres. Co-ordination can be explicit through a negotiation protocol, e.g. ACAS, or implicit through the sharing of common resolution rules, e.g. force fields. With a planning resolution, a distributed planning technique is required. The case of simultaneous resolution and planning raises the issue of efficiency: should both aircraft plan as if the other aircraft is moving (i.e. only half of the separation, and if it does not move separation will be broken), or as if the other aircraft is not moving (i.e. full separation and if it does move, twice separation standard will be obtained, hence with is wasteful in particular in the vertical plane).

Sequential: aircraft solve the conflict according to a sequence order. The sequence order can be defined in two ways: centralised as usually done in Robotics, or decentralised as done with Visual Flight Rule (VFR), Extended Flight Rules (EFR). The order can depend on several parameters such as the constraint level of aircraft, e.g. EFR, or the availability in term of workload for the pilot.

4.4 Co-ordination domain

The aircraft considered for resolution can range from the two aircraft immediately in conflict, to a "cluster" of aircraft that are directly or indirectly in conflict [1][8].

ACAS logic and VFR priority remains limited to pairwise situations. EFR in an extension of VFR indicating aircraft currently in a resolution process, and is therefore thought to handle non complex multiple aircraft encounters.

The force field techniques naturally handle clusters of aircraft by taking advantage of the additiveness on force vectors. The priority assignment rules based on "token allocation" proposed by [1] can be seen as an extension of VFR and EFR that is also capable to handle clusters of aircraft.

4.5 Examples

Some representative examples of conflict detection and resolution approaches are given in Table 1.

A typical example of an intent based approach is [10] which relies on transmission of Trajectory Change Points (TCPs) extracted from the FMS. To ensure consistency between aircraft manoeuvres, EFR have been set up, defining priorities between aircraft in conflict. Pilots must plan their trajectory for up to 6 minutes in advance according to their priority. Following this planning approach, [1] proposes an extension of the EFR towards complex multi-aircraft situations, using a "token allocation strategy" for setting priorities along with an optimisation technique based on A* algorithm.

On the opposite side, other studies [36] are based upon a reactive approach where all aircraft move at the same time following tactical advisories (no explicit co-ordination rule, no planning).

Resolution strategy → / Co-ordination strategy ↓	Reactive	Planning
Simultaneous	*ACAS, Force field*	*Distributed planning*
Prioritised	*VFR*	*EFR and trajectory planning, Token allocation and A* planning*

Co-ordination domain → / Co-ordination strategy ↓	Pairwise	Multiple
Simultaneous	*ACAS*	*Force field*
Prioritised	*VFR*	*EFR, Token allocation*

Table 1. Representative examples.

5 Conclusion

A wide range of studies has been carried out so far in the domain of delegation of separation assurance to aircraft, leading to various concepts, applications and techniques. For analysing and linking this different studies, a general framework has been proposed leading to the description of three dimensions: (1) the operational aspects with the notion of "level of delegation", (2) the cockpit aspects through the notion of "level of assistance", and (3) the system point of view through intent, resolution and co-ordination characterisation. Finally, using this taxonomy, some representative examples have been described, giving hints on aspects that require further research.

Acronyms

ADS-B	Automatic Dependant Surveillance – Broadcast
ACAS	Airborne Collision Avoidance System
ASAS	Airborne Separation Assurance System
ATC	Air Traffic Control
ATM	Air Traffic Management
CDTI	Cockpit Display of Traffic Information
CNS	Communication, Navigation, Surveillance
EFR	Extended Flight Rules
FMS	Flight Management System
TCAS	Traffic alert and Collision Avoidance System
TCP	Trajectory Change Point
TIS-B	Traffic Information Service – Broadcast
TMA	Terminal Manoeuvring Area
VFR	Visual Flight Rule

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