Priority Rules in a Distributed ATM

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Priority rules are often considered to be a promising method how to reduce number of maneuvering aircraft in the envisioned new (distributed) ATM separation modes. In the presented paper, we discuss priority rules that have been so far used, developed and suggested for the autonomous aircraft concept. The objective is to consider their advantages and drawbacks as well as factors that should be reflected in the definition of such rules for self separation operations in the future ATM. The relation between the priority rules on one side and applied conflict resolution strategy and information sharing process on the other side is also described. The paper concludes by a suggestion how to overcome the drawbacks of the existing priority rules through a combination of several operational elements.

I. Introduction

THE ongoing transformation of Air Traffic Management (ATM) both in Europe (SESAR)[1] and in the US (NextGen)[2] aims to increase the capacity and the efficiency of the current systems while maintaining high level of safety. One of the envisioned means is the introduction of new separation modes based on an increased role of flight crew in the separation management process[3]. It is envisioned that in addition to a decrease of the ATC controller's workload, a direct involvement of flight crew in the ATM (using advanced onboard Airborne Separation Assistance Systems (ASAS)) will allow to solve potential conflicts in a more efficient way.

The latter assumption is based on the fact that a distributed ATM allows a straightforward implementation of user (flight crew, airlines, ...) preferences, and that ASAS can profit from accurate information available from onboard sensors. However, the efficiency of distributed operations may be considerably degraded by the operational aspects. While in the centralized ATM, the ATC controller assesses the global situation and can select the aircraft that is most suitable to maneuver such a selection can be rather complicated in the absence of a central authority. In the existing research of distributed operations (so-called ASAS Self Separation), this issue is typically solved by requiring all conflicting aircraft to maneuver for urgent conflicts (safety prevails efficiency) and by introducing priority rules for the conflicts detected sufficiently in advance. The purpose of these rules is to determine (unambiguously) which of the conflicting aircraft is required to maneuver thus avoiding the excessive maneuvering by other involved aircraft. The effectiveness of such priority-based approach depends strongly on the extent to which the ATM objectives are incorporated in the definition of priority rules.

The presented work was performed within the EC-funded project iFly[4]. The paper starts by a short introduction into autonomous aircraft concept and the scope of the iFly project. Subsequently, the use of priority rules in self separation operations is discussed as well as the results of the previous research. Finally, we propose an operational concept which aims to overcome the drawbacks of the existing approaches and we demonstrate its application through a simple illustrative example.

II. Distributed ATM and the iFly Project

As already mentioned, the transition from a centralized ATM system to a distributed air traffic control brings many benefits but also specific problems to be solved. Some of the most critical issues include:

- How to coordinate simultaneous maneuvering of multiple aircraft.
- How to avoid maneuvering of excessive number of aircraft.
- How to avoid excessive maneuvering of single aircraft.
- How to incorporate the global strategic aspects into ASAS distributed control.

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Typically it is assumed that the operational rules for self separating operations will be defined in the form of so-called Autonomous Flight Rules (AFR) in analogy with the existing Visual Flight Rules and Instrumental Flight Rules. A nice overview of the ASAS research and concepts can be found, for instance, in Ref. 5, or Ref. 6.

The key enabler of a distributed ATM system is an effective information sharing process providing each aircraft with information about its surrounding traffic. This is achieved by an extensive use of data link technologies, such as Automatic Dependent Surveillance – Broadcast (ADS-B) or Traffic Information Service – Broadcast (TIS-B). In addition, both the European SESAR[7] and the US NextGen[8] ATM Concepts of Operations envisions an enhancement of the strategic ATM using Trajectory-Based Operations (TBO) to face the trajectory prediction uncertainty problem. Dynamic sharing of 4D (i.e., position and time) trajectory (the term Reference Business Trajectory (RBT)[*] is used thereafter) will be enabled by the System Wide Information Management (SWIM) system which will incorporate ground infrastructure and air-ground data links network.

The goal of the iFly Concept of Operations[9] is to enable a safe and efficient autonomous flight through an en-route (segregated) airspace. This en-route phase of flight is ended by a flight constraint (3D point with a time interval) at the entry point of the destination TMA in order to reflect the existence of ATM strategic flow constraints. The onboard separation management is enabled by a periodic broadcast of state and intent[†] information by all autonomous aircraft, and it is based on a two-level Conflict Resolution (CR) process according to the estimated time to predicted Loss of Separation (LoS)[‡]. When the time for maneuvering is shorter than at predefined threshold, all conflicting aircraft must maneuver and the applied maneuvers shall be coordinated through so-called implicit coordination. The latter is based on the use of compatible algorithms that generate complementary maneuvers for conflicting aircraft. Conflicts detected in advance (with respect to the time threshold) are solved using the priority rules principle. In both cases, the involved aircraft will not broadcast any additional information and there is no requirement for any additional individual data exchange.

III. Priority Rules in ASAS Operations

The primary purpose for the use of priority rules in distributed ATM is to avoid excessive maneuvering of all conflicting aircraft in the situations when the potential conflict is detected sufficiently in advance. In addition to the benefits it brings to airspace users, the use of priority rules also contributes to the stability of the overall ATM system. As the initial RBTs are planned and optimized taking into account all relevant traffic, frequent trajectory changes increase the probability of the need for tactical maneuvering.

When speaking about priority rules, two main research questions typically arise: how to define the priority of aircraft, and when and how this priority number should be used during autonomous operations. The two aspects are tightly connected and they cannot be solved independently. Although the priority rules usually reduce the number of aircraft that are required to maneuver, if their definition is not coherent with the operational context they may not lead to an effective solution of the conflicting situation. This is particularly apparent when priority rules are applied to a conflict among multiple aircraft.

A. Priority Number

One of the most complete studies on the definition of priority rules for autonomous aircraft concept was performed under the FREER (Free-Route Experimental Encounter Resolution) project[10]. Within this project there were defined so-called Extended Flight Rules (EFR) for autonomous operations which allow to decide about the priority between any two aircraft in the conflict.

The FREER strategy for determining the priority is based on a consideration of three main components:

- Maneuverability,
- Availability (flexibility according to the navigation constraints),
- Distance to predicted LoS.

In addition, the priority also reflects the actual category of operation, such as normal operations, emergency, no communications, etc. It may be stated that the most of subsequent ASAS projects (including iFly) considers very similar factors for the priority definition and the main difference lies in the way how they are evaluated.

As mentioned in the previous section, the definition of priority cannot be done without considering the operational context of its use. In particular, the applied coordination among conflicting aircraft directly affects

[*] This term originates from SESAR where it is used for trajectory information shared during the flight.
[†] Intent is a part of the intended trajectory used for tactical ATM tasks. Its accuracy is usually higher than the accuracy of the whole RBT (which is used mainly for strategic tasks). The considered look-ahead time horizon is typically about 10-20 minutes.
[‡] Collision avoidance is assumed independent of ASAS functions and is provided in the same way as in the ATC-managed airspace.

how the conflicting situation can be reflected in the priority number. As each autonomous aircraft has different awareness zone (area from which it receives the traffic information broadcasted by other aircraft), and due to stochastic character of the environment, it is practically impossible to guarantee the same onboard assessment of the situation by all involved aircraft. This issue is illustrated in Figure 1 showing how the predicted Closest Point of Approach (CPA) may vary among conflicting aircraft. Among multiple error sources contributing to this problem (flight technical error, navigation error, communication delay, etc.) the most important contribution is in general associated with the trajectory prediction uncertainty.

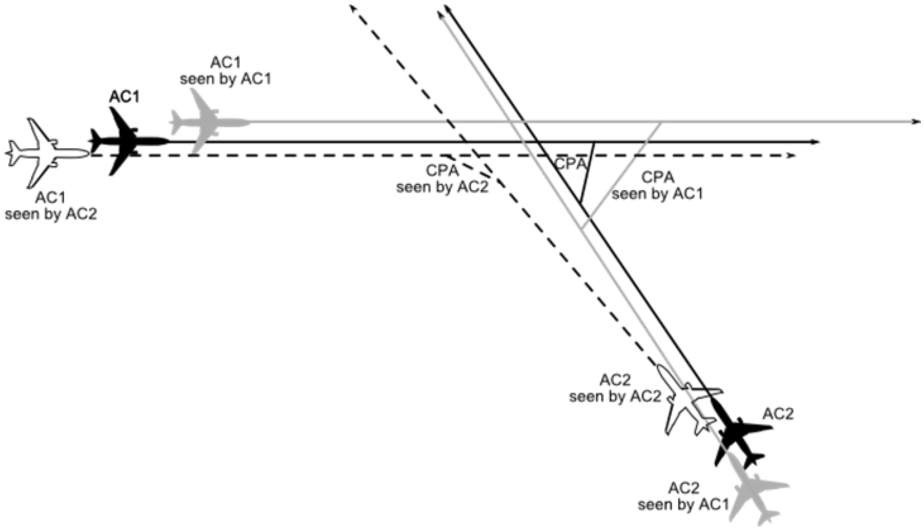

Figure 1: Illustration of possible inconsistencies in the detection of Closest Point of Approach (CPA) during a pair-wise conflict.

From above follows that if the priority number is based on a dynamic onboard evaluation of the situation, then the application of priority rules requires an explicit coordination (communication) among involved aircraft in order to synchronize the resulting priority numbers. A crucial drawback lies in the fact that the explicit coordination among aircraft during the Conflict Resolution (CR) process inserts additional safety hazards into the system behavior and considerably increases the complexity of the problem (see, e.g., Ref. 5).

On the other hand, if a specific conflict configuration is not taken into account, it may happen that maneuvering of a lower priority aircraft is less effective than an alternative solution based on maneuvering of the aircraft with higher priority[11]. In the limiting case, such a solution may even not exist. In Ref. 11 it is proposed to solve this issue by allowing a priority reversal process, however, such approach again requires an explicit communication among conflicting aircraft.

B. Priority Rules in Multi Aircraft Conflict

In addition to determining which aircraft should maneuver in a pair-wise conflict, the priority rules may be used also in solving multi-aircraft conflicts. Such approach was adopted, for instance, in the FACES program[12] where the priority numbers of involved aircraft are used to build a sequence in which the conflict is solved (FACES implements this strategy in the form of a token allocation process). According the rules, each aircraft in the sequence is then responsible to avoid the trajectories of aircraft with higher priorities.

This method again requires an explicit communication among involved aircraft and it is not very flexible with respect to the new events that can appear during the conflict solution. Another important aspect that is very often missed out is the fact that the ASAS is defined as a pilot's supporting tool. This has an important impact because the solutions proposed by ASAS automation are not executed immediately but they are first evaluated by the flight crew. They can be modified, and they are really executed only after a pilot's decision, which brings in an important delay before the new intent can be broadcasted to the surrounding traffic. These aspects were studied in detail, e.g., in Ref. 13 and 14 and according the research it is reasonable to consider up to 2 minutes for these purposes. A possible accumulation of these delays in the CR sequence, together with the achievable range of ADS-B coverage (about 90 NM) may considerably reduce the applicability of a sequential approach for solving conflicts with many aircraft.

IV. Proposed Approach

Within this section we propose an operational concept based on the use of priority rules to solve conflicts between two aircraft and on a set of operational rules to coordinate trajectory changes among multiple aircraft. Contrary to the approaches described above, the proposed concept does not require explicit coordination among conflicting aircraft. Moreover, it allows a straightforward implementation of strategic ATM objectives into distributed operations (the priority is determined centrally on the ground).

Note that although the ideas presented in this section are based on the initial iFly Concept of Operations[9], they result from our subsequent work so they go beyond (extend) this concept. The basic elements of the iFly's approach adopted in the following are:

- CR is not based on explicit coordination among conflicting aircraft.
- Priority rules are used only for mid-term conflicts (the exact definition is to be determined but it should cover the conflicts with more than 3-5 minutes to the predicted LoS), short-term conflicts being solved using implicit coordination.
- The conflict resolution for a mid-term conflict is performed as a search for a new conflict-free trajectory taking into account the valid strategic constraints and (preferably) minimizing deviations from the actual RBT.
- Priority and category of operation is broadcasted as an aircraft state characteristic.
- It is assumed that the actual RBT is available in the automated ground system (SWIM).
- ASAS is designed as a flight crew's supporting tool. In particular, there is considered a time lag between the moment when the possible tactical maneuver(s) is presented to flight crew and the start of the maneuver execution. This time is required for pilot's decision process.

It is considered that flight rules discussed in this section will use two aircraft characteristics: priority number as discussed below and the category of operation (normal, emergency, no communications, etc.). The basic operational difference is that while the priority number is used only to determine who should maneuver in a pair-wise conflict, the category of operation affects also the conflict resolution process for other types of conflict (including short-term). Nevertheless, within this paper only the conflicts among aircraft in the category of normal operation are considered.

A. Priority Number

As discussed earlier, in the absence of explicit synchronization among conflicting aircraft, priority should not be based on the dynamic onboard evaluation of the detected situation. On the contrary, it should be determined in advance and therefore on the basis of widely shared information. Taking this requirement into account, it seems logical to associate the priority (which may vary along the trajectory) of an autonomous aircraft with its actual RBT and allocate the priority determination to a centralized (ground) application.

If the priorities are to be defined by a centralized application based on shared RBTs, it is crucial to identify which factors (comparing, for instance to the FREER approach[10]) could be taken into account in this way. The first important benefit of a centralized application is that it allows introducing global strategic objectives into a distributed tactical control. Let us illustrate it on the scenario discussed in Ref. 11: the case of a traffic flow crossing by an isolated aircraft. Obviously from a strategic point of view it is more reasonable to ensure that the isolated aircraft has lower priority in order to avoid tactical maneuvering inside the flow. Another factor which may be easily evaluated from RBT is the "availability" (with respect to navigation and other strategic constraints) considered within the FREER project. Finally, RBTs allow evaluating (taking into account the trajectory prediction uncertainty especially considering time) the geometrical maneuverability of aircraft.

As the initial RBTs are determined to be (a priori) conflict-free, they are not suitable to assess a dynamically arisen conflicting situation(conflicts usually appear due to the trajectory prediction uncertainty and the stochastic behavior of the environment). Therefore the main limitation of the RBT-based priority concept (comparing to the FREER approach) is the absence of the actual (dynamic) maneuverability with respect to the detected conflict, and this factor must be implemented by different means within the ASAS system. For instance, within the iFly project an envisioned detection of areas with high air traffic complexity[15] (as a part of the Conflict Detection function) provides this functionality . For comparison, a straightforward evaluation and prediction of aircraft maneuverability is considered in this context in NASA[16]. In both cases, a detection of a complex area (or reduced maneuverability) triggers a trajectory change and the potentially hazardous situation is thus solved in advance.

Comparing the proposed concept with the priority reversal process considered in Ref. 11, our approach introduces a two-level process which aims to avoid the failure of the priority-based conflict resolution:

- Strategic objectives are incorporated in the definition of the priority by a centralized application. In this way, many situations such as, e.g., traffic flow interacting with an isolated aircraft can be handled.
- Complexity or maneuverability prediction aims to prevent the situations when an aircraft cannot find the solution of the detected conflict.

If (despite the above mitigation) the aircraft with lower priority fails to find a solution, the conflict should be solved through the short-term conflict resolution process (using implicit coordination). Of course safety and effectiveness of this approach must be still verified through the validation and detailed safety assessment.

B. Multi Aircraft Conflict

Contrary to, e.g., a token allocation strategy[12] we do not consider the use of priority number for a coordination of multi aircraft conflict solution. Instead we suggest an alternative approach based on broadcast of the intention to change own trajectory. The basic idea is: each aircraft, which aims to modify its RBT (and therefore its intent received by surrounding aircraft), will have to share this intention by a simple flag in its state broadcast together with a time stamp saying when the flag was first issued. In the following we will use the term **change mode** for this aircraft state. Operational rules described below specify when the execution (and broadcast) of the new trajectory can be started and how to handle the coordination when multiple aircraft need to maneuver at the same time. The key benefit of this method is that it can be used without any explicit communication among involved aircraft.

C. Trajectory Change Initiation

Our approach suggests that an aircraft has to modify its trajectory whenever it detects any of the following events:

- A pair-wise conflict with an aircraft with higher priority number,
- Conflict with more than one aircraft,
- Passing through an area with high air traffic complexity.

Note, that a trajectory change is not triggered by a conflict with an aircraft, which is in a change mode already. In fact, as the maneuvering aircraft is looking for a new conflict-free trajectory the conflict should be inherently solved by its expected maneuvering.

D. Coordination among Maneuvering Aircraft

When more than one aircraft need to modify their trajectories (e.g., multi aircraft conflict, or close conflicts of disjoint pairs of aircraft), the changes are sequenced based on the First Come First Served principle taking into account the time stamp of switching to the change mode. The operational rules introduce three time constraints for this process:

- After switching to the change mode, ASAS system will wait for the time *M* (in order of seconds) before initiating a search for new trajectory. The purpose of this lag is to take into account communication delays of potential change messages by other aircraft. ASAS has to verify if there is no other aircraft in the change mode with an older time stamp. Such an aircraft would be given preference in the transition to the change mode.
- When in the change mode, there is a maximum time *I* (initial estimation of this time is about 2 minutes) until which the new trajectory must be broadcasted and its execution started.
- In addition, when some of the surrounding aircraft is already in the change mode, own aircraft cannot switch to the change mode sooner than in time *S* (in order of tens of seconds) after the latest time stamp of the already maneuvering aircraft. The reason is that if two aircraft switch to the change mode immediately one after another, the latter one could receive an updated trajectory of the former one only shortly before its own time interval *I* elapses. Hence, it would not have enough time to incorporate the newly received information into its own trajectory generation process.

E. Operations Modeling

In order to model the considered priority-related operations, we introduce four basic aircraft states (or more precisely groups of states):

- The BASIC state is a state in which the ownship is flying its RBT and has no detected conflicts (either with at least one aircraft, or with a complexity area) or restrictions related to potential trajectory changes (e.g., due to another aircraft in change mode).

- The NOMAN group contains states which differ from BASIC but in which the ownship is not required to maneuver. For example, detection of one aircraft in change mode (with or without conflict with the ownship).
- The PRIO group contains states driven by priority rules, i.e., these are states in which there is exactly one conflict detected with an aircraft not in the change mode.
- The MAN group contains states in which the ownship is required to maneuver. There are all situations with multiple conflicts (with aircraft not in change mode) and situations in which at least one complex area is detected.

The change mode introduced earlier represents a transition state (process) within our model. The simplified state diagram of the considered operations for the ownship is shown in Figure 2.

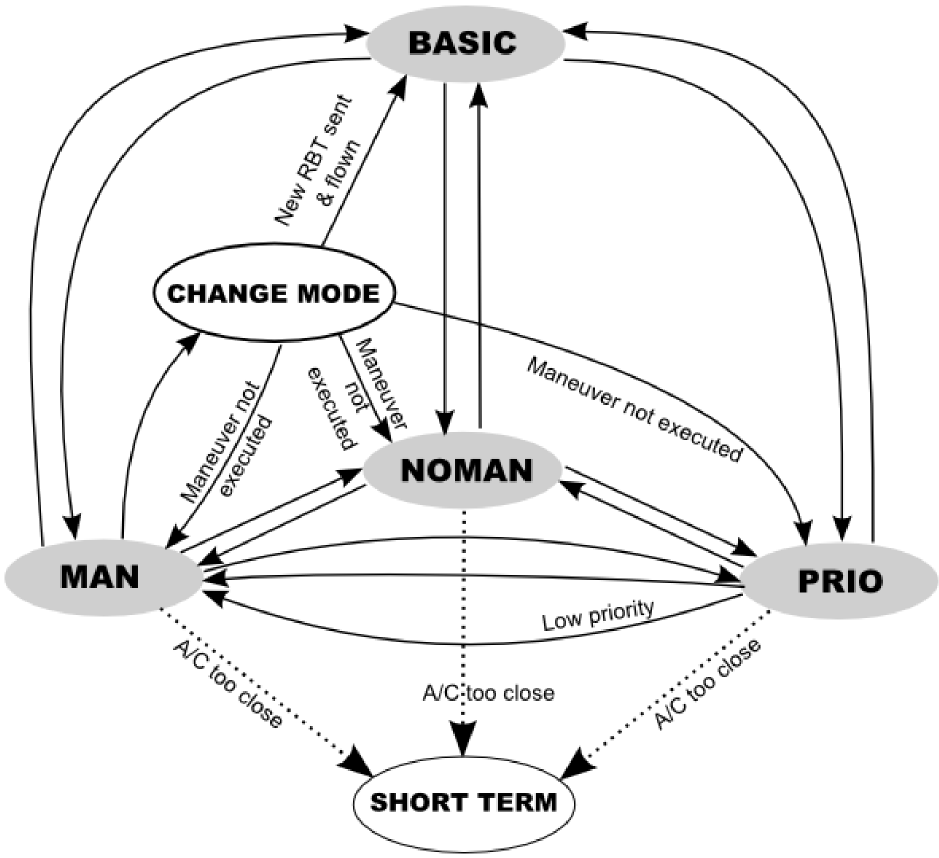

Figure 2: Simplified state diagram of the proposed mid-term CR process.

The ownship is initially in the BASIC state. Once a conflict is detected, the ownship switches to another state. We can assume that the conflicts are detected consecutively (one after one). With each newly detected conflict, the ownship can change its state: the states that can be entered in such a way are MAN, NOMAN and PRIO. Consider the following events:

- Detection of a complex area,
- Detection of one conflict,
- Detection of more conflicts,
- Detection of (at least one) conflict with an aircraft in change mode,
- Detection of (at least one) aircraft in change mode but not in conflict with the ownship.

These events can occur separately or simultaneously, which gives 23 states in total, divided for our purposes into the three groups defined above: MAN, NOMAN and PRIO.

If the priority rule assigns the maneuvering task to the ownship, the state is switched to MAN and the ownship attempts to maneuver. This is initiated by switching to the change mode. This attempt may or may not be successful (the whole process is described in detail in the following section (see Figure 3)). If the attempt is successful and a new conflict-free RBT is generated and flown, a transition back to the BASIC state is made. If, on the other hand, the new maneuver cannot be performed for some reason, the (ever evolving) situation of the ownship is reassessed and the state is switched accordingly either back to MAN or to PRIO or NOMAN in case of luckily positive evolution.

Note that the transitions between states MAN, PRIO, NOMAN and BASIC are both ways. This is because the situation is continuously evolving and sometimes it can evolve in a positive way, that is, a conflict can disappear without any action from the ownship crew. However, this theoretical arrow in the state diagram cannot be considered as an option for the crew who should initiate a maneuver attempt as soon as able. This timely and active behavior may pay off in terms of being given priority in new RBT selection, as seen in Figure 3.

If conflicting aircraft get too close to each other, the conflict must be solved as a short term conflict however, this process goes beyond the scope of this paper.

F. Process Model of a Trajectory Change

Figure 3 presents a flow chart of a maneuvering attempt by the ownship. Basically, there are two possible situations in which an aircraft can try to maneuver: no other aircraft in the change mode detected (left branch), or some aircraft already in the change mode detected (right branch).

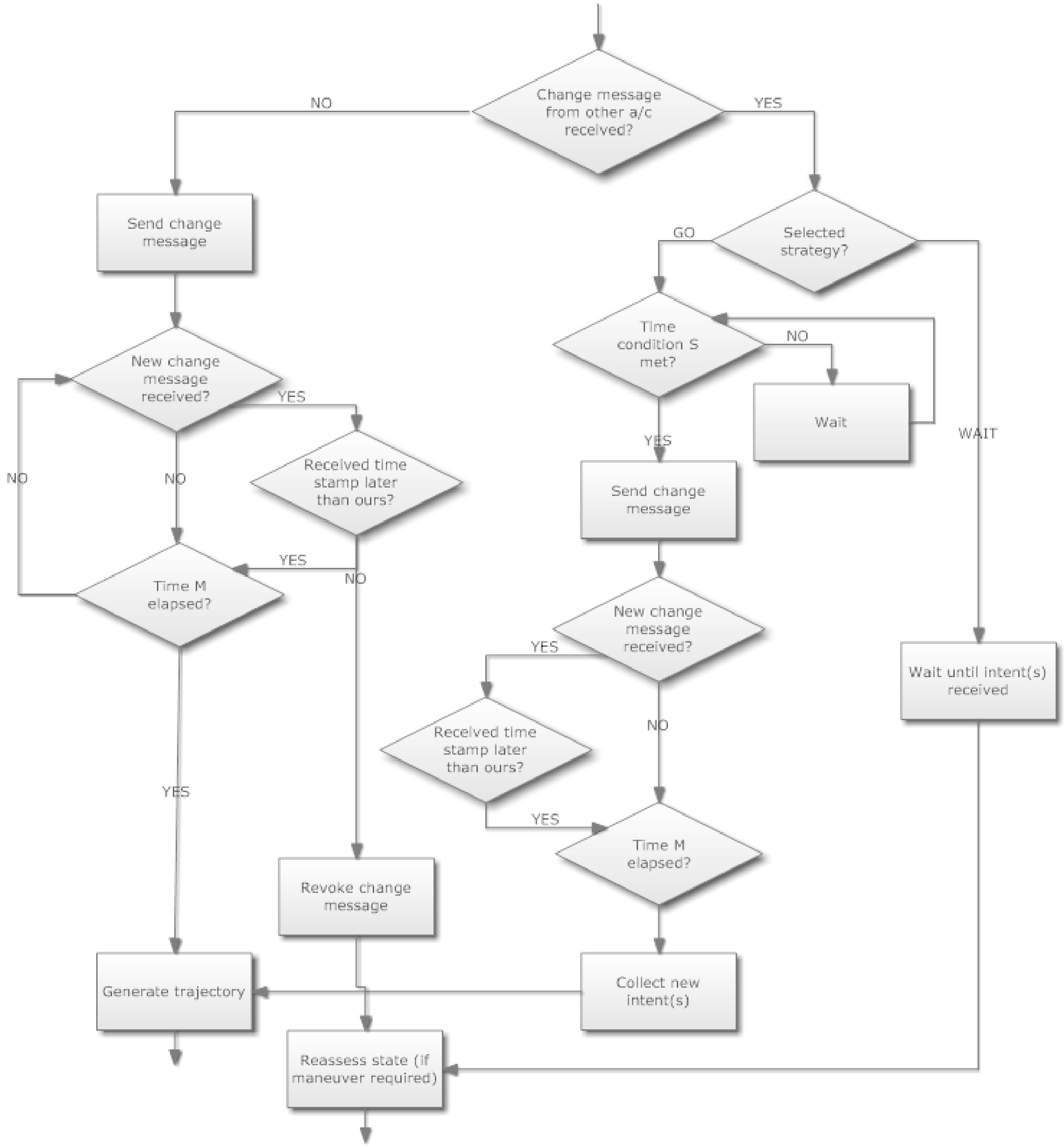

Figure 3: Flow chart of a maneuvering attempt according the proposed coordination approach.

If the ownship has not detected any other aircraft in the change mode, it can immediately issue a change message. Now the predefined time interval *M* must pass during which the ownship periodically checks for change messages from other aircraft. If none arrives within the predefined time interval *M*, new RBT can be computed, issued and executed. If a change message is received within time interval *M*, the ownship (and the other aircraft as well) check the time stamps of message issuance. The oldest time stamp wins and its sender is given the privilege to ignore the other one's maneuver attempt. In such a case the other change message must be revoked.

The ownship may want to attempt maneuver even in a situation in which it has already detected other aircraft's change message (let us label the corresponding time stamp *T0*). Still, there are two options. The ownship may choose to wait for the other aircraft's new RBTs, especially if the time stamp(s) indicate(s) that it will be sent soon. Alternatively, the ownship may issue a change message at time $T0+t$ (where $S < t < I$), and be ready to accept new trajectory at time t after the reception of the new intent of other aircraft at the latest.

Note that the operational rules only specify until when the new trajectory has to be broadcasted to other users, that is, between *M* and *I*. In particular, onboard system may solve the situation and propose the possible solutions already while waiting to other aircraft new intent broadcast. In this way, flight crew may monitor and interpret the traffic situation already in advance, which can simplify (and shorten) the decision making process after the reception of other aircraft's intent(s). Furthermore, as it is considered that ASAS should be typically able to provide more than one possible solution, it is very probable that at least some of them will not be affected by a new intent of already maneuvering aircraft. Pilot's experience and enhanced situation awareness (for instance, provided by Cockpit Display of Traffic Information (CDTI)[17]) can further help in anticipating which solution(s) will stay untouched by maneuvering aircraft.

V. Example of Application

Let us consider a three-aircraft example (Figure 4). Suppose aircraft A has detected two conflicts. None of the conflicting aircraft, B and C, is in the change mode. Hence A is requested to maneuver and issues a change message. Suppose that aircraft B receives the change message from A just before detecting the Conflict 1 itself. Aircraft B switches to NOMAN, since it is in conflict only with an aircraft in the change mode. It can rely on the avoidance action from A and do nothing.

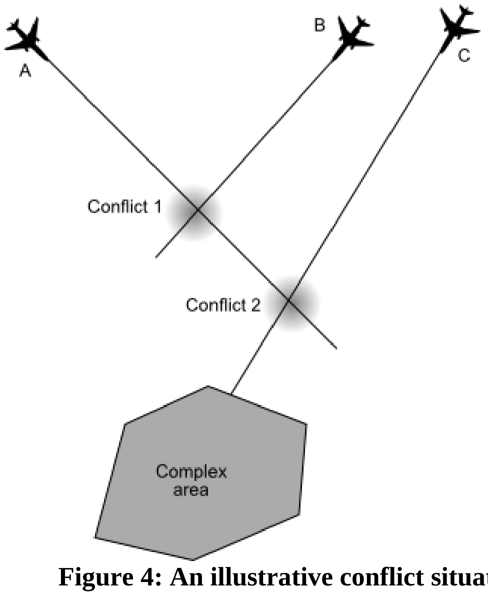

Figure 4: An illustrative conflict situation.

Suppose aircraft C has not received information about its conflict with A so far (due to the inconsistency in situation assessment as discussed earlier). Nevertheless, it has detected a complex area, which requires maneuvering. Therefore aircraft C switches to the change mode (i.e., it broadcasts its change message). Accidentally, the change messages from A and C are sent approximately in the same moment. After receiving each other's change messages and comparing time stamps of issuance, aircraft A and C both know that it was A who sent its message first. Aircraft C has to revoke its change message immediately.

Let us now have a close look at the next evolution. Aircraft A keeps checking other aircraft's change messages for time stamps comparison (such as the one sent by C) until time interval *M* elapses. After this time it can be assumed that all aircraft in the ADS-B range of A have received its change message, and no more accidental coincidence in change messages follows. After *M* elapses, aircraft A plans its new trajectory so that it is ready to issue it, at the latest, predefined time I after sending the change message.

Before aircraft A publishes its new trajectory, aircraft C decides not to wait for it. Instead, it waits only until time *S* elapses from the time stamp of the change message of A. Immediately after that, aircraft C sends a new change message. When the new trajectory of A is known to C, it can generate its own new trajectory. Note that A has incorporated both the original trajectories of B and C into its planning since it is avoiding both the conflicts. It is the responsibility of C to take into account the new trajectory of A. As a consequence, C is likely to continue as originally planned through the place of Conflict 2, and avoid only its complex area later on.

In such a way, B does not have to maneuver at all. C has high likelihood to choose only minor deviation since it only has to avoid the complex area and the new trajectory of A, which is now conflict-free. Aircraft A has also some room for optimization since it has the privilege to choose and execute the maneuver long time in advance before both the conflicts approach.

VI. Conclusion

In this paper we present an operational concept focused on the use of priority rules in distributed ATM. The key difference between the proposed approach and previously published methods lies in the absence of explicit communication among involved aircraft. This considerably reduces the complexity of the CR process, in particular, when more than two aircraft are involved in the conflict. In this paper, the priority number is identified as a mean of incorporating global strategic objectives into autonomous aircraft operations and is associated with widely shared trajectory information (RBT). Note, that in the future ATM systems (SESAR, NextGen) it is planned that this up-to-date information will be available in the ground-based information sharing system (SWIM), which makes a potential implementation of a centralized application providing the strategic priority allocation service for autonomous aircraft rather straightforward. The proposed approach was developed as a possible extension of the initial Concept of Operations defined within the iFly project, but it is not supported by the appropriate validation activities so far. Therefore, the follow-up work should consist in simulations of the considered operations and a comparison of obtained performance and safety characteristics with the existing alternative approaches (e.g., priority reversal or token allocation methods).

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References

[1]SESAR programme web page, URL: http://www.eurocontrol.int/sesar/.

[2]NextGen program web page, URL: http://www.faa.gov/about/initiatives/nextgen/.

[3]ASAS-Thematic Network 2 (ASAS-TN2) Work Package 3, "ASAS Application Maturity Assessment", v.3.0, ASAS-TN2/WP3/Report/3.0, 7th March 2008.

[4]iFly project web page, URL: http://ifly.nlr.nl.

[5]Hoekstra, J. M., "Designing for safety: the Free Flight Air Traffic Management Concept", doctoral thesis, NLR TP-2001-313, Nov 2001.

[6]Wing, D., "A Potentially Useful Role for Airborne Separation in 4D-Trajectory ATM Operations", AIAA-2005-7336, ATIO, Washington DC, 2005.

[7]SESAR Definition Phase, Deliverable 3, "The ATM Target Concept", DLM-0612-001-02-00a, September 2007.

[8]Joint Planning and Development Office, "Concept of Operations for the Next Generation Air Transportation System", v. 2.0, 13 June 2007.

[9]Cuevas G., Echegoyen, I., Garcia, J. G., Cásek, P., Keinrath, C., Bussink, F., and Luuk, A., iFly Deliverable D1.3, "Autonomous Aircraft Advanced (A3) Concept of Operations", to be published at URL: http://iFLY.nlr.nl.

[10]Duong, V. N., Hoffman, E., and Nicolaon, J.-P., "Initial Results of Investigation into Autonomous Aircraft Concept (FREER-1)", *Proceedings of the 1st USA/EUROPE Air Traffic Management Research and Development*, Saclay, 1997.

[11]Irvine, R., "Comparison of Pair-Wise Priority-Based Resolution Schemes Through Fast-Time Simulation", *8th Innovative Research (INO) Workshop*, Bretigny, 2009.

[12]Alliot, J. M., Durand, N., and Granger, G., "FACES: a Free Flight Autonomous and Coordinated Embarked Solver", *Air Traffic Control Quaterly*, Vol. 8 (2000), p. 109-130.

[13]Consiglio, M., Hoadley, S., Wing, D., Baxley, B., and Allen, D., "Impact of Pilot Delay and Non-Responsiveness on the Safety Performance of Airborne Separation", *The 26th Congress of International Council of the Aeronautical Sciences (ICAS)*, Anchorage, Alaska, 14-19 September 2008.

[14]N.A. Doble, R. Barhydt, and J.M. Hitt II, "Distributed conflict management in en route airspace: human-in-the-loop results", *24th Digital Avionics Conference*, Washington DC, 2005.

[15]Brázdilová, S. L., Cásek, P., and Kubalčík, J., "Airspace Complexity for Airborne Self Separation", *CEAS 2009 European Air and Space Conference*, Royal Aeronautical Society, Manchester UK, 2009.

[16]Idris, H., Vivona, R., Garcia-Chico, J., and Wing, D., "Distributed traffic complexity management by preserving trajectory flexibility", 26th Digital Avionics Conference, 2007.

[17]RTCA SC 186, "Applications Descriptions for Initial Cockpit Display of Traffic Information (CDTI) Applications", DO-259, 13th September 2000.