Identification of Spatiotemporal Interdependencies and Complexity Evolution in a Multiple Aircraft Environment

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Abstract—To support future automated transitions among the ATM safety nets, this study elaborates identification of the complex traffic scenarios based on the concept of aerial ecosystems. As an extension of the TCAS operational domain and evolving from the separation management towards collision avoidance layer, the concept has been developed as a stepwise algorithm for identification of cooperative aircraft involved in the safety event – detected conflict, and negotiating their resolution trajectories before the ecosystem deadlock event occurs, in which at least one aircraft stays out of a conflict-free resolution. As a response to this threshold, the paper examines generation of both acceptable and candidate resolution trajectories, with respect to the original aircraft trajectories. The candidate trajectories are generated from a set of tactical waypoints and a return waypoint to the original trajectory. Described methodology has been practically implemented to one ecosystem scenario, characterizing its evolution in terms of the intrinsic complexity. By introducing the heading maneuver changes and delay in the resolution process, the results have shown how the scenario complexity is increasing, especially affected by the states of two aircraft in the initial conflict. Furthermore, it has been demonstrated an evolution in the amount of the acceptable and candidate trajectory solutions, for which the minimum complexity value is satisfied. A goal of the study was to explore the lateral resolutions capacity at certain moments and its timely decrement.

Keywords-ecosystem identification; complexity; candidate resolution trajectories; spatiotemporal interdependencies; aircraft manoueverability

I. INTRODUCTION

An increased traffic demand and trajectory deviations due to environmental uncertainties impact on the ATC workload at tactical level [1], [2]. With respect to the closest point of approach (CPA) between two aircraft in conflict, this level is timely framed between two safety thresholds: the mid-term conflict detection (MTCD), that is activated approximately 15 minutes before the aircraft reach the CPA, and the short-term conflict alert (STCA), triggered approximately 120 seconds before the CPA. This point is operationally defined as an estimated 4D point at which a distance between two conflicting aircraft reaches a minimum value. The air traffic control (ATC) system provides the separation management (SM) services by guiding one or more aircraft out of their trajectories. If the STCA fails, two conflicting aircraft potentially enter a collision avoidance (CA) layer that is characterized by a non-ATC separation provision, but directives coming from on-board the aircraft [3].

In near-term operations, the ground-based safety nets (STCA) need to work optimally in the future ATM environments. The Airborne Collision Avoidance Systems are globally operable and need to be optimized compatible with existing systems [4]. The Traffic Alert and Collision Avoidance System (TCAS), as an airborne autonomous system, demonstrates an excellent performance in the pairwise and multi-treat encounters, but suffers from a lack of an extended operational logic due to well-reported induced collisions in some complex scenarios [5]. Moreover, the TCAS resolution advisories (RAs) may be inconsistent with the standard ATC procedures [6], and produce a gap in integration of the SM, at the tactical level, and collision avoidance (CA), at the operational level. Therefore, new research lines are required towards development of the collaborative and decentralized SM layer, on which the human behavior and automation will be fully aligned. That anticipates an operational integration of the safety procedures in such a way that any pair of aircraft involved in a conflict, together with the surrounding trajectories of the neighboring aircraft, behave as a stable conflict-free air traffic system. Furthermore, the integration should include the critical information on the feasible resolution trajectories (RTs), proposed throughout development of decision support tools.

Potential incoherence between the SM and the CA could occur due to differences between the ATC directive after STCA, and a TCAS advisory. In many complex situations, the ATC system does not timely provide separation services after STCA that activates a TCAS alert. As a TCAS sense is based on a set of logic advisories, considering only nearby airspace volumes, the advisory is frequently opposite from an ATC directive,

which is considered from a larger, sector-based volume. This situation may produce an ambiguity in the pilot-in-command decision process, and provoke a higher severity of the conflict event [7]. Moreover, TCAS advisories sometimes require more demanding manoeuvres for the crew, taking into consideration the flight efficiency aspects [8].

The proposed concept of aerial ecosystems – a tactical air traffic system - presents a new operational framework that intends to solve the time horizon paradigm in a multiple aircraft environment. The principal function is to identify the system causality and decrease a solution complexity at the SM level, not triggering the TCAS alerts for any potential state changes. An ecosystem, as a multi-agent system [9] presents a set of aircraft with the trajectory-amendment and decision-making capability, whose trajectories are identified inside a computed airspace volume - cluster - and are causally involved in a safety event through identification of the spatiotemporal interdependencies (STIs). The STIs present a product of potential avoidance maneuvers among the aircraft involved in the safety event. The ecosystem creation is based on a pairwise conflict detection, computation of the operational airspace volume (clustering), and search for the surrounding traffic (ST) aircraft who might have the STIs with conflicting aircraft. An ST exploration could be done timely, in advance, by applying the proper functional metrics at the certain timestamps, preceding the conflict event. This position should guarantee the coherence between the SM and CA layers and the functionalities before and after the STCA threshold. An important ecosystem objective is a deployment of the negotiation interactions among the ecosystem aircraft for finding the best comprise in the resolution process. From the flight-efficiency aspect, the RTs should be as closest as possible to the reference business trajectories. Furthermore, the multi-agent, decision-making process inside the ecosystem should assure a reliable generation of the conflict-free resolutions comparing to the separation actions performed at the strategic level, that must include more intent data for the RT generation.

This paper elaborates the ecosystem identification procedure from an operationally created cluster, and detection of the STIs between each pair of aircraft, belonging to the ecosystem. The identification is performed using a specific set of the parametric values. A comprehensive state space analysis of the detected interdependencies has been used for a method definition of the RT generation. Then, it is further described a selection of the candidate RTs among each pair of the ecosystem members, and analysis of their acceptance based on a given complexity value. Those are trajectories triggered only in case that agreed resolutions trajectories cannot be obtained before the ecosystem deadlock event is reached. For the flight efficiency purpose as well as coherence with the TCAS function in vertical plane, only the lateral resolutions are considered. Explained methodology has been practically implemented on a real traffic scenario and obtained results have been gathered for a post-analysis and the potential improvements.

In addition to this introductory section the article comprises five other sections. Section II defines the conceptual problem of complex traffic scenarios when severity of the conflict event

arises. Section III describes methodology for the ecosystem identification and STI generation for development of the tactical conflict management, while Section IV describes the algorithm for generation of the candidate resolutions before the deadlock event occurs. Section V analyses the simulation results of an ecosystem scenario at a certain complexity level, and compares the pairs of the candidate resolutions at three time stamps during the ecosystem evolution. Concluding remarks and further research notes are provided in Section VI.

II. PROBLEM DEFINITION

This section describes a need for introduction of the ecosystem concept and challenges in generation of the RTs, when a time evolution affects an available conflict-free airspace, and results a decrement of the system solutions.

A. Time horizon problem

The transitions from the SM to the CA require a time capacity in which the standard separation minima (SSM) is fully maintained, i.e. $SSM_H = 5$ NM and $SSM_V = 1000$ft, where SSM_H presents the horizontal separation distance while SSM_V denotes the vertical one. The resolution of a pairwise aircraft encounter in a multi-aircraft environment frequently meets the lack of a maneuvering time for a succeeding conflict event. In this case, the conflict usually evolves into an induced collision, which is a subject to the implementation of different TCAS RAs operable in the vertical, but also in the horizontal plane [10].

To illustrate the concept of an induced collision, it is first considered a simple traffic scenario, with two evolving and one cruising aircraft. Figure 1 illustrates a scenario with three aircraft, namely A/C01, A/C02 and A/C03. A/C01 and A/C02 are flying over trajectories that generate a predicted conflict, while A/C03 presents an ST aircraft.
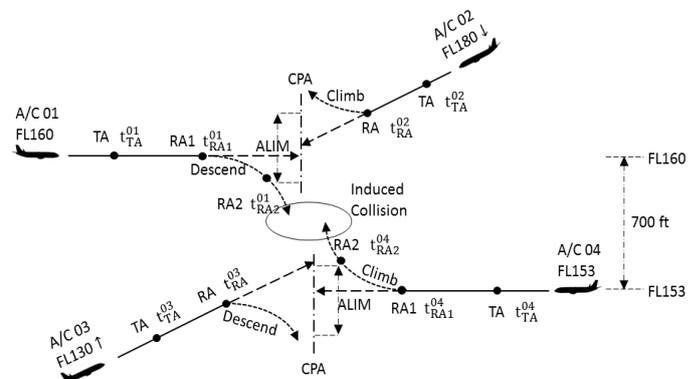

Figure 1. Induced collision as a product of previously solved conflict

A/C01 is in cruising mode while A/C02 starts descending in the opposite direction from A/C01, which assumes a direct approch to A/C01 with a loss of height. On the other hand, A/C03 is climbing close to identified encounter. As it can be seen, based on TCAS logic [11], [12], the conflict between A/C01 and A/C02 is triggered after activation of the traffic advisories (TA), at the time stamps t_{TA}^{01} and t_{TA}^{02}, and then followed by the corresponding RAs, successfully resolved at the

time stamps t_{RA1}^{01} and t_{RA}^{02}. The minimal required vertical separation, ALIM, has been successfully achieved around the CPA.

As the CA layer activates in approximately 60 seconds before the CPA, once resolved conflicts produce very high uncertainty in guidance over the amending RBTs. After its amendment, A/C01 enters a protected zone of A/C03 [13], [14], and generates a new conflict, denoted as an induced conflict. It is characterized by an instantaneous RA alert, while the aircraft is still performing requested resolution manoeuver and not resuming to its RBT [15]. In this case, A/C01 was automatically alerted by the succeeding RA at t_{RA2}^{01}, but also A/C03 with an instantaneous RA at t_{RA}^{03}, with an advisory "Descend". However, due to insufficient time for the appropriate succeeding maneuvers two aircraft came into the induced collision. Therefore, the ST aircraft might introduce a higher level of uncertainty in geometry of the pairwise encounter.

B. Ecosystem evolution and deadlock event

The key issue in the resolution of an ecosystem is to identify the time limit above which an induced collision could emerge due to a conflict avoidance maneuver. This threshold is called the ecosystem deadlock event (EDE) and depends on the geometric profiles of the RBTs, the flight configuration (cruise, climb, descent) and the encounter dynamics (closure rates). The EDE is computed and triggered by the ATC. It presents a time instant at which at least one ecosystem aircraft cannot perform any feasible maneuver leading to the conflict-free solution. Instead, an induced collision could emerge. The time frame between the ecosystem identification instant and EDE is approved for the resolutions negotiation. This negotiation is implemented by means of the agent technology in which each aircraft is enhanced by an agent that follows the airline business model, used to identify preferred amending maneuver. This technology provides the right framework to support the negotiation between the ecosystem members to reach a resolution consensus avoiding the ATC intervention which does not consider the airline preferences. Therefore, the objective is to explore the STIs among each pair of aircraft and provide an information on the conflict intervals within the time frame, mentioned above.

The ecosystem evolution toward computed EDE is characterized by a continuously decreasing rate in the number of potential resolutions. In other words, the prolongation in the agents' negotiation forces the aircraft to continuously follow-up their RBTs which negatively affects a total number of the conflict-free trajectory amendments. A time lost in the negotiation is indirectly proportional to the available ecosystem maneuvering space. Figure 2 illustrates the ecosystem evolution over three time windows, TW1, TW2 and TW3, in which each subsequent window is a sub-window of the previous one. TW3 denotes a CA window whose edges present the EDE moment. Aircraft reaching this ecosystem instant on their RBTs are not a subject to the ATC separation provision, but the TCAS activation. Therefore, any agreed (cooperative) maneuvers inside the TW3 will not provide the conflict-free amendments with respect to the SSM.
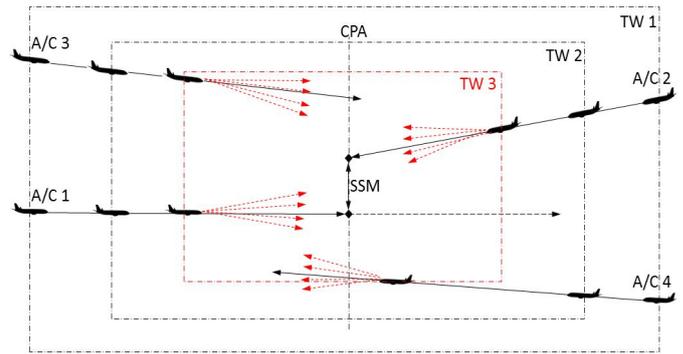

Figure 2.   Ecosystem evolution towards EDE

Figure 3 shows a theoretical decreasing rate of the conflict-free solutions *S* over the ecosystem time. It can be noted a higher drop in the number of solutions that occur until the TW1, and then follow-up with a lower decreasing rate until the TW2. *S* approaches to zero value when the ecosystem enters the TW3.
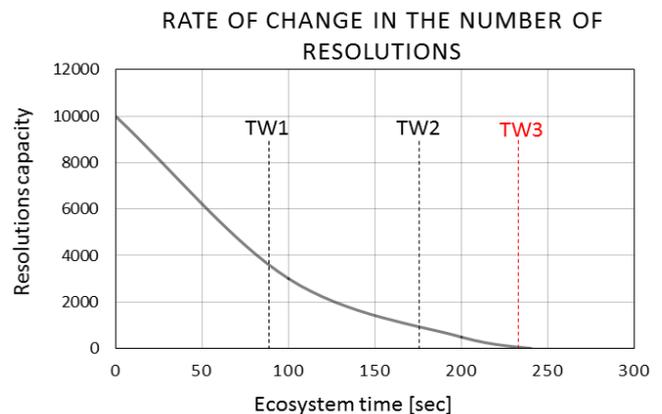

Figure 3.   Rate of change in the number of resulting manoeuvers

As a response to non-agreed resolutions before the EDE appears, the compulsory resolutions must be activated. The computational method continuously searches for them, aiming to eliminate TW3 in any preceding moment.

III.   METHODOLOGY FOR ECOSYSTEM IDENTIFICATION

This section describes the ecosystem identification algorithm and method for the STI detection. The algorithm relies on the concept hotspot-cluster-ecosystem that foresees four steps [16]:

1.   extraction of en-route traffic at tactical level,

2.   creation of the ecosystem scenarios from detected pairwise conflicts,

3.   clustering of the airspace volumes that comprises a set of the ST aircraft nearby detected conflicts, and

4. identification of those ST aircraft having the STIs with the conflicting aircraft; they become the ecosystem members.

A. Ecosystem identification

The following subsection describes Step 4 from the clustered aircraft. As a response to the time horizon problem, the ecosystem considers a longer operational time characterized by an advanced conflict prediction interval, i.e. lookahead time (LAT), in which the conflicting aircraft obtain a set of information on the ST aircraft in nearby airspace, and all together cooperatively interact in a decision-making process.

The aircraft clustering is built on a pairwise conflict using the spatial measures, the horizontal (H_{CB}) and the vertical (V_{CB}) cluster buffer. By default, H_{CB} is set to 15 NM and V_{CB} to 3000 ft. Within a box-shaped volume and by the filtering procedure of the corresponding traffic data, any waypoint belonging to the ST trajectory identifies a cluster aircraft [16], but also potential ecosystem member. Figures 4 and 5 illustrate one clustering configuration projected in the horizontal and vertical plane, respectively. There is a predicted conflict between aircraft A/C1 and A/C2 with three identified ST aircraft, i.e. ST1, ST2 and ST3. A/C1 and A/C2 are positioned at their conflict detection points from which the cluster volume has been created, in line with adopted spatial constructors.
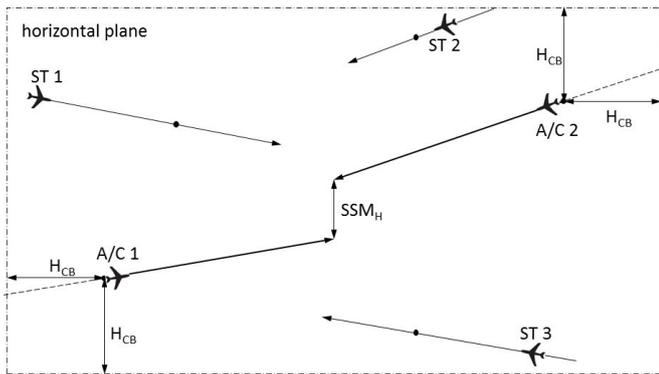

Figure 4. Horizontal projection of the aircraft clustering
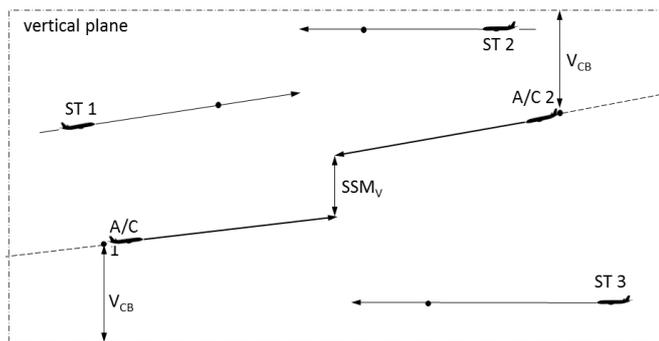

Figure 5. Vertical projection of the aircraft clustering

The ecosystem algorithm determines if a cluster ST aircraft evolves into an ecosystem member for which a loss of the SSM with any of two conflicting aircraft would occur if this aircraft performs a given amending maneuver at any moment during the LAT. Considerably, the ecosystem identification is a spatiotemporal category as the applied maneuver generates conflict intervals with neighboring aircraft [17]. Maneuverability is applied in both the horizontal and the vertical plane and defined with the set of parametric values:

- m_1: Left heading change with a deflection angle $\Delta hd_L = +30°$;
- m_2: Right heading change with a deflection angle $\Delta hd_R = -30°$;
- m_3: Climb at vertical rate $ROC = +1000$ ft/min and minimal flight path angle $\gamma_C = +2°$;
- m_4: Descent at vertical rate $ROD = -1000$ ft/min and minimal flight path angle $\gamma_D = -2°$.

The specified values have been used for the testing of identified ecosystems. However, they might be a subject to changes in a further analysis. Figure 6 illustrates an example of the identification procedure where A/C1 and A/C2, being in predicted conflict, identify the ST aircraft, namely A/C3 and A/C4, by applying certain avoidance maneuvers, m_3 and m_4.
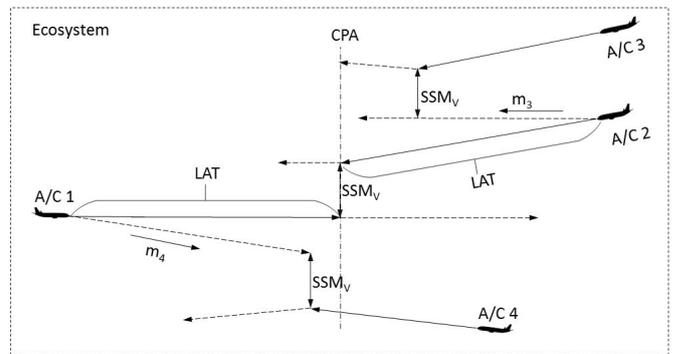

Figure 6. Ecosystem identification

B. STI detection

The algorithm computes the time windows for each ecosystem member, inside which any potential cooperative or non-cooperative, horizontal or vertical, maneuver could produce a loss of the SSM. Those windows are sub-intervals of the LAT and the number of conflict maneuvers within each window is obtained as per defined time rate (by default, one second) along each RBT. Figure 7 shows an example of the conflict interval generated using left heading change. Conflict interval 1 denotes a period in which A/C1 performing given maneuver generates a continuous conflict with A/C3.
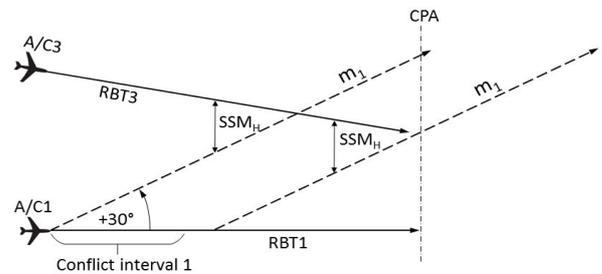

Figure 7. Conflict interval for a single RBT applying $\Delta hd_L = +30°$
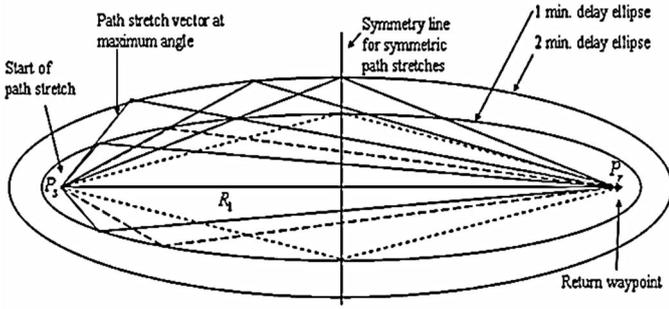
Figure 8. Locus of the tactical waypoints for introducing a given delay to a trajectory [18]

The number of STIs (N_{STI}) between the pairs of aircraft is obtained using four types of amending manoeuvers, explained above, and one additional, m_0: RBT follow-up. In this study, therefore, five types of manoeuvers are counted for, i.e. $M = 5$. Each interdependency contains one or more conflict intervals, and a total number of the conflict intervals (I) must satisfy the following condition:

$$I \leq \frac{N_A (N_A - 1)}{2} M^2 \qquad (1)$$

where N_A denotes the number of ecosystem members, and M^2 is a derived property that presents total number of maneuvering combinations applied to one pair of aircraft. An example of the STI structure is presented in TABLE I. It consists of the STI identifier, the combninations of two interdepedednt flight identifiers, the maneuvering combination and the conflict interval. One STI among one pair of aircraft might generate more conflict intervals due to different maneuvering combinations.

TABLE I. STI STRUCTURE

STI_ID	Interdependent aircraft	Maneuvering combination	Conflict interval [sec]
STI 1	A/C1 – A/C2	$m_0 – m_0$	$t_{11} – t_{12}$
	A/C1 – A/C2	$m_4 – m_3$	$t_{21} – t_{22}$
	A/C1 – A/C2	$m_2 – m_4$	$t_{31} – t_{32}$
STI 2	A/C1 – A/C3	$m_0 – m_0$	$t_{51} – t_{52}$
	A/C1 – A/C3	$m_0 – m_3$	$t_{61} – t_{62}$

IV. METHOD FOR GENERATION OF THE CANDIDATE RTs

A complexity of the ecosystem evolution is evaluated based on the decreasing (perishable) rate in number of the candidate RTs over the ecosystem time. A resolution candidate trajectory is defined based on generation of a set of the tactical waypoints (TWPs) and a return waypoint to the RBT.

Those TWPs are calculated from an ellipse-based trajectories scheme, in which the aircraft is placed at one foci (a starting point) and a returning point is allocated to the opposite foci. Thus, the TWPs are placed on the different ellipses generated by fixing a certain amount of delay to be introduced to the flight (Fig.8). Then, a pair of the candidate trajectories is evaluated one against another by computing the evolution of the intrinsic complexity as defined in [19]. If two candidate trajectories have a complexity value larger than the values analogous to the TCAS TAs, it is rejected.

In addition, if the proposed trajectories result in the separation infringements, they are also rejected. The generation of the RTs is limited to a set of heading changes, including maintaining the RBT. These heading changes vary from -30° to +30° for each aircraft, with steps of 10°. In addition, the delays that could be introduced can go up to 4 minutes, with a 1-minute step. Finally, the number of the available RTs in each timestamp includes those that can be issued at that specific moment, and all available RTs that are computed for the future timestamps until the end of the conflict interval.

V. SIMULATION AND ANALYSIS OF RESULTS

The main data source for simulation and verification of the obtained results was Demand Data Repository 2 (DDR2), developed and maintained by EUROCONTROL. Traffic scenarios are generated using historical data, the selected flight plans (planned 4D trajectories) in the so-called *s06 model 1* (m1) data format [20]. In this study, s06 trajectories are considered as RBTs. The following data have been used for testing:

- historical traffic dated on 24/08/2017;
- traffic extraction in the selected period, 08:00 – 09:00 (28800 – 32400 seconds);
- operational environment above FL300.

After analysis of the simulated traffic, an ecosystem scenario with 5 members has been selected (TABLE II). Four interdependencies have been detected among the ecosystem members, as structured in TABLE III. The time frame for the ecosystem process was slotted between 29159.00 and 29421.29 seconds. For the graphical presentation purpose, these time thresholds are converted in such a way that 29159.00 corresponds to 0 seconds, and 29421.29 to 262.29 seconds.

TABLE II. ECOSYSTEM TRAJECTORIES

Flight ID	4D structure of ecosystem trajectories							
	φ_1 [°]	λ_1 [°]	h_1 [ft]	t_1 [sec]	φ_2 [°]	λ_2 [°]	h_2 [ft]	t_2 [sec]
A/C1	39.0000	-3.542	36000	0.00	39.5278	-3.489	36000	262.29
A/C2	39.0462	-3.874	36000	0.00	39.5506	-3.593	36000	262.29
A/C3	39.1109	-4.334	36000	0.00	39.5142	-3.814	36000	262.29
A/C4	39.7103	-4.075	39000	0.00	39.2788	-4.448	39000	262.29
A/C5	38.9277	-4.570	36000	0.00	39.3302	-4.052	36000	262.29

TABLE III. STI STRUCTURE

	Ecosystem STI output		
STI_ID	Interdependent aircraft	Maneuvering combination	Conflict interval [sec]
STI_1	A/C1 – A/C2	0 – 0	0.00 – 188.26
	A/C1 – A/C2	0 – 3	0.00 – 188.26
	A/C1 – A/C2	0 – 4	0.00 – 188.26
	A/C1 – A/C2	2 – 1	0.00 – 188.26
	A/C1 – A/C2	3 – 0	0.00 – 188.26
	A/C1 – A/C2	3 – 3	0.00 – 188.26

Ecosystem STI output			
STI_ID	**Interdependent aircraft**	**Maneuvering combination**	**Conflict interval [sec]**
	A/C1 – A/C2	3 – 4	0.00 – 188.26
	A/C1 – A/C2	4 – 0	0.00 – 188.26
	A/C1 – A/C2	4 – 3	0.00 – 188.26
	A/C1 – A/C2	4 – 4	0.00 – 188.26
	A/C2 – A/C3	0 – 0	0.00 – 51.48
	A/C2 – A/C3	0 – 3	0.00 – 51.48
	A/C2 – A/C3	0 – 4	0.00 – 51.48
	A/C2 – A/C3	3 – 0	0.00 – 51.48
STI_2	A/C2 – A/C3	3 – 3	0.00 – 51.48
	A/C2 – A/C3	3 – 4	0.00 – 51.48
	A/C2 – A/C3	4 – 0	0.00 – 51.48
	A/C2 – A/C3	4 – 3	0.00 – 51.48
	A/C2 – A/C3	4 – 4	0.00 – 51.48
	A/C2 – A/C5	2 – 0	120.00 – 130.28
STI_3	A/C2 – A/C5	2 – 3	120.00 – 130.28
	A/C2 – A/C5	2 – 4	120.00 – 130.28
STI_4	A/C3 – A/C4	2 – 4	90.00 – 91.01

Figure 9. describes the evolution of the acceptable and the candidate RTs over the LAT. The horizontal axis represents the larger conflict interval given by TABLE III. On the left-hand axis, it is represented the number of acceptable RTs (columns on red) and a total number of the candidate ones that have been generated. The axis is represented on a log10-scale. The complexity for the solution that provides the minimum one is plotted in black, with its values on the right-hand side. If there is not an acceptable resolution trajectory, then the complexity is marked as 10 (maximum acceptable complexity).
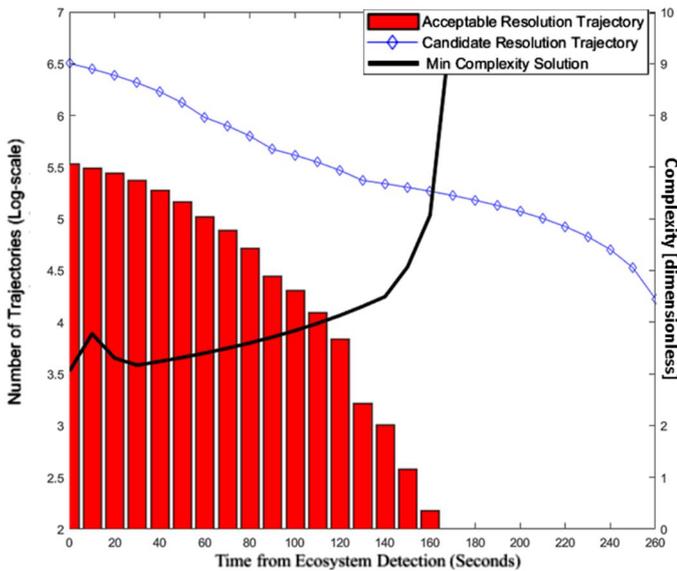

Figure 9.   Evolution of acceptable and candidate RTs and complexity of the the minimal complexity solution

The situations at relevant timestamps are presented on the following figures (Fig. 10, Fig. 11 and Fig. 12). Figure 10 represents the situation at the initial timestamp, Figure 11 the situation when 100 seconds passed, and finally, Figure 12 analyzes timestamp after 160 seconds. The chosen set of the RTs have been plotted in each figure, representing the 48-seconds projection when the resolution should be implemented.

The aircraft position and trajectories are represented by a stereographic projection where the tangential point is located at the initial point of A/C1.
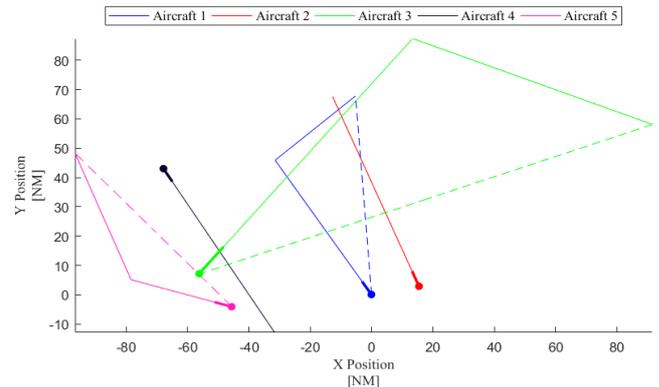

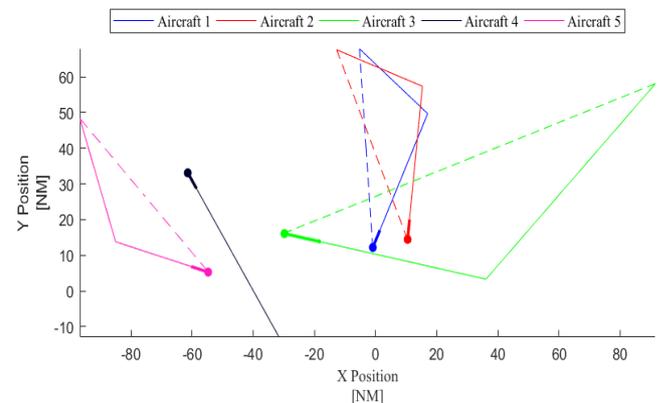Figure 10. Resolutions scenario I: Timestamp 0, lower complexity level

Figure 11. Resolutions scenario II: Timestamp 100-seconds, medium complexity level (A/C1 and A/C2)
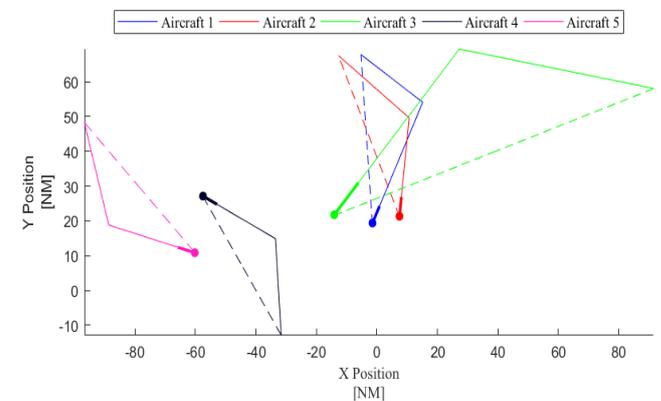

Figure 12. Resolutions scenario III: Timestamp 160-seconds, maximum complexity level (A/C1, A/C2 and A/C3)

It can be observed how the complexity trend increases from the timestamp of 20 seconds, after a peak that is generated as a result of the initial states of Aircraft 1 and Aircraft 5. It is arguable that the solution provided at t = 160 sec would solve the situation, as the RTs have not been generated with realistic models for the aircraft dynamics, so the no-solution timestamp would be even earlier.

It can be observed in which period the aircraft could be allowed to negotiate among themselves for finding a solution compromise, but also how it is mandatory to maintain the possibility for the compulsory resolutions if the ecosystem members do not agree on a set of trajectories. This time instant should be located before the complexity evolution changes its behavior from the linear to the exponential one.

VI. CONCLUSIONS

This paper describes the automation-based conflict management process for a smooth transition from SM to CA layer by introducing the ecosystem concept. The goal of developed methodology was to determine the existence of ecosystems at the tactical level in the monitored airspace volume and their complexity levels coming from different traffic scenarios. For this purpose, the stepwise approach has been deployed by identifying the safety events in a high-dense traffic environment, in which the causal analysis could be performed. The exploration of the available and acceptable RTs, using the ellipse-based scheme, has been further elaborated with respect to the SSM, and by introducing some dynamic properties, like the heading changes and delay in the resolution initialization. Smooth transition from the ecosystem membership identification to the acceptable candidate resolutions generation provides very valuable insight of the STI structure and a complexity level at a certain moment in the ecosystem evolution.

The results show how the number of the available RTs perishes over time, for a fixed returning point of the intended trajectory. They also illustrate an exponential evolution of the complexity, due to chosen metric for its evaluation. The projected figures at the relevant timestamps display how the RTs become tighter and more complex. Taking into consideration the certain aircraft maneuverability, tested within computed conflict intervals over the ecosystem LAT, the solutions can be compared on basis of the heading changes and delay propagation, followed by the minimal complexity value. Nevertheless, more results obtained from the study and like those presented in this paper, have demonstrated that solutions not only prevent the separation infringements in the horizontal plane, but also provide the compatible aircraft states with TCAS function in which the TAs would not get triggered.

Further research needs to be carried in more directions: an analysis of the multi-thread conflicts with respect to time to the CPA, a reduction of the computational time and an incorporation of the fine trajectory predictions for the ecosystem detection and resolution algorithms, as well as an extension of the parametric values for more robust STI testing. Moreover, some research efforts will be made toward development of the agents' negotiation process and prediction of the deadlock instant.

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