A COMPARATIVE ANALYSIS OF DIFFERENT METHODS FOR IDENTIFICATION OF THE EVOLUTION OF NUMBER OF POSSIBLE CONFLICT-FREE AIRSPACE CONFIGURATIONS INCLUDING MULTIPLE AIRCRAFT AND SINGLE CONFLICT

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ABSTRACT

Continuous increase in the traffic density over the certain enroute sectors provokes many situations in which a loss of separation minima (SM) between two aircraft occurs. Although, this loss is predicted well in advance, giving a proper look-ahead time (LAT) for a detection function, the resolution of such an event may lead to a new conflict situation due to dynamics of surrounding traffic aircraft. A multi-agent system framework can deal with these cases.

This work presents three different complexity indicators that can be used to shape the social behavior of the agents. Simulation results show that the proposed indicators can suggest drastically different nature of the same ecosystem, therefore further investigation of the correlation of the proposed indicators to the actual complexity is necessary.

Keywords: ecosystem, feasible solutions, opportunity costs, conflict maneuvers

1. INTRODUCTION

Continuous increase in the traffic density over the certain en-route sectors provokes many situations in which a loss of separation minima (SM) between two aircraft occurs (Bouarfa, Blom, Curran, and Everdij 2013: Kochenderfer, Holland, Chryssanthacopoulos 2012; Kuchar, Yang 2000). Although, this loss is predicted well in advance, giving a proper look-ahead time (LAT) for a detection function, the resolution of such an event may lead to a new conflict situation due to dynamics of surrounding traffic aircraft (Livadas, Lygeros, Lynch 2000; Murugan, Oblah 2010; Tang, Piera, Ling, Fan 2015). Namely, some resulting maneuvers of the conflicting aircraft can induce new loss of SM with nearby aircraft in which new LAT for detection can be significantly reduced. Consequently, a collision risk in this case is often at a higher level, which usually requires more demanding avoidance maneuver for the pilot-ingenerating also inefficient trajectory command, segments.

At present, an upgraded Traffic Alert and Collision Avoidance System (TCAS II v7.1), has been designed for operations in the traffic densities of 0.3 aircraft per squared nautical mile (AGENT Project Team 2016; Tang, Piera, Ling, Fan 2015). It demonstrates excellent performances for the pairwise encounters, as well as the great improvements for multi-thread encounters, taking different flight configurations (cruising and evolving aircraft) into considerations. However, a TCAS logic shows some operational drawbacks due to limited number of resolution advisories, currently resulting in the vertical flight profile change only (Enea, Porretta 2012; Ramasamy, Sabatini, Gardi, Kistan 2014). Moreover, the well reported induced collisions in many traffic scenarios show a high probability of occurrence. Thus, there is a challenge to investigate and implement a new operational framework which will improve and extend TCAS functionalities at both tactical and operational level.

This paper relies on a new research in the ATM automation framework: the concept of ecosystems (AGENT project team 2016; Radanovic, Piera, Koca, Saez 2017). Ecosystem presents a set of aircraft, with self-automated capabilities, that form a cost-efficient separation management system for finding the best compromise in resolution trajectories. The goal is to transform the ecosystem aircraft into intelligent agents that can communicate with each other to safely make the best use of existing airspace capacity. The concept has been developed to handle a robust conflict management process considering aircraft performances, and consistent solutions in front of the scalability problems.

The study particularly compares three indicators of the evolution over time of the number of generated feasible resolution trajectories. All three of them address in common a maintenance of the SM criteria, the causal relationships, namely spatiotemporal interdependencies, and the metrics used for identification of the ecosystem aircraft through state space exploration.

The first indicator produces the accumulative number of conflict-free system configurations over time. The 4D time-space is discretized and the possibilities are counted.

In order not to count solutions which although feasible, they are under no criteria desirable, the second one is proposed. In this case, using a greedy search process the method identifies and counts the closest conflict-free configurations for each path of the search tree. The third indicator is following a similar approach to the second one, but instead of counting the provided solutions, it measures the provided clearance for the given solutions.

In addition to this introductory section, the paper comprises five other sections. Section 2 includes some background, Section 3 describes three methods to generate the estimations, while Section 4 discusses simulation results and compares them. Section 5 gives concluding remarks and directions for the follow-up research.

2. BACKGROUND

2.1. Ecosystem concept

As said in the introduction this paper relies on concept of the ecosystem. An ecosystem is defined as a set that includes two aircraft in conflict between them and their surrounding traffic.

An aircraft A is part of the surrounding traffic if there exist a feasible maneuver that performed during the existence time (chosen to be 5 minutes) of the ecosystem by some member B of the ecosystem, or by aircraft A itself, will induce a new conflict in the ecosystem between aircraft A and B.



Figure 1 - Example of ecosystem

Essentially the framework tries to solve the conflicts by considering also the other aircraft that might be affected by a given deviation set of maneuvers in a pairwise conflict. In doing so, the ecosystem aircraft are treated as intelligent agents that can communicate with each other to safely make the best use of existing airspace capacity.

2.2. The necessity for complexity analysis

The multi-agent framework is capable to provide an acceptable solution, a conflict-free configuration of the system. However, the decision making is done in real time and therefore the system is time critical, therefore some information regarding the complexity of the scenario can be handy (Lyons 2012; Prandini, Piroddi, Puechmorel, Brázdilová 2011). A complex, not easy to solve scenario calls for a more collaborative behavior of the aircraft-agents, while on the other hand a not so complex ecosystem can allow agents to seek longer for a solution that fits better their criteria.

In these conditions, an indicator of the system's complexity is desired. Some attempts to quantify this complexity where done (Delahaye, Puechmorel 2000). This work proposes 3 more complexity indicators that can provide more explicit information.

2.3. Model Assumptions and Restrictions

In the considered scenarios, some assumptions are made. Firstly, the aircraft trajectories during the existence of the ecosystem are linear segments.

Secondly the maneuver space is discretized in space and time, which means aircraft can perform maneuvers with a certain deviation angle from the original trajectory and these maneuvers can be performed only at discrete time instances. The maximum angle deviation is assumed to be 30° and the increment 5°. The time increment is taken 1 second.



Figure 2 – Possible maneuvers performed by an aircraft and how they can affect interdependencies with another one

figure

Lastly the possible taken maneuvers should be synchronous, i.e. all the performed maneuvers that will be taken to resolve the conflict should be taken at the same time from all aircraft members.

3. INDICATORS DESCRIPTION

3.1. Full search of the discretized state space

The first discussed approach deals with the evolution in time of the number of possible configurations of the system that are conflict free. The pairwise interdependencies are identified in space and time and using this information the configurations with at least a conflict are identified. Subtracting this value from the total amount of

possible configurations at each time instance will give us the desired quantity.

Indicator 1 Model

- 1. For each pair of aircraft identify the intervals during which interdependencies for different performed maneuvers are present
- 2. Using this information and the discretization parameters calculate the conflict-present system configurations
- 3. Calculate the total amount of possible system configurations
- 4. Calculate the number of conflict-free configurations by subtracting quantity calculated at step 2 from the quantity of step 3

3.2. Greedy search of the discretized state space

The previous indicator although it has some good properties, it has some drawbacks as well. One of them is that it needs to explore the whole discretized state space.

Moreover, some of the counted configurations, although feasible are at no way optimal, desirable, or necessary to consider. More specifically, let's consider an ecosystem with 3 members. AC1 And AC2 are in conflict and AC3 is surrounding traffic.

Let's further assume that AC1 going left 15° provides or AC1 going left 15° and AC3 climbing both provide conflict-free configurations of the system. Although both are visible, clearly option 1 is better than option 2.

To try to avoid this redundant information, indicator 2 is proposed.

Indicator 2, using a greedy search of the state space, gives an indication the number of conflict-free configurations of the system. More specifically, starting with the 2 conflict-aircraft, a maneuver is applied to one of them. If the system is conflict free, the configuration is counted as a solution and restarting from the original system configuration, other possibilities are sought. If on the other hand the maneuver produces a new conflict, a new maneuver is introduced to the traffic aircraft involved in the new conflict.

| Indica | for | 2 | Model | |
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for each time instance:

- 1. Select 1 of the conflict aircraft
- 2. Perturb its trajectory using a maneuver from the set of maneuvers
- 3. if there is no conflict in the system:
- 4. count 1 more solution
- 5. if there are more unexplored solutions:
- 6. repeat for a different maneuver
- else if there is unexplored aircraft left:
 repeat for the new aircraft

| 9. | else: |
|---------|--|
| 10. | end |
| 11. els | se if there is unexplored aircraft left: |
| 12. | apply perturbation to it and repeat |
| 13. els | se: |
| 14. | end |

3.3. Accumulator of the conflict-free perimeters

Indicator 2 provides some information regarding the depth of the search by counting solutions. Another approach is introduced by indicator 2 and proposed in this section.

The key idea is that instead of counting the solutions themselves, the length of the arc formed taking as center the point where the aircraft performs the maneuver and as radius the distance that the aircraft will travel from that point until the end time of the ecosystem for each solution is measured. Given this information the evolution over time of the cumulative arc length is represented.



Figure 3 – Illustration of how a given maneuver performed at different time instances provides different amount of clearance

Indicator 3 Model

| for e | each time instance: |
|-------|--|
| 1. | Select 1 of the conflict aircraft |
| 2. | Perturb its trajectory using a maneuver from |
| | the set of maneuvers |
| 3. | if there is no conflict in the system: |
| 4. | calculate the length of the formed arc |
| 5. | Add the length to the total length |
| 6. | if there are more unexplored solutions: |
| 7. | repeat for a different maneuver |
| 8. | else if there is unexplored aircraft left: |
| 9. | repeat for the new aircraft |
| 10. | else: |
| 11. | end |
| 12. | else if there is unexplored aircraft left: |
| 13. | apply perturbation to it and repeat |
| 14. | else: |
| 15 | end |

The main drawback of indicator 3 is that it does not provide any information regarding the number of solution at each time instance. However, a combination of indicator 2 and 3 can give us a clearer picture of the dynamics of the system.

4. SIMULATIONS RESULTS

The following section discusses some simulation results obtained from analysis of two ecosystems. The ecosystem trajectories are graphically presented in a 3D Euclidean space, with latitude and longitude measured in [km] and altitude in [ft]. The results show the cumulative number of the feasible trajectories over the ecosystem time.

A. Ecosystem 1







Figure 5 – Indicator 1 results for ecosystem 1

As can be seen from Figure 4, ecosystem 1 is composed of three aircraft in an evolving encounter: two of them in descending configuration and the third with a climbing approach. Figure 5 illustrates an amount of the feasible trajectories. It can be noted that this quantity follows a constant trend during the large percentage of the ecosystem time. The maximum number of 1200 trajectories is triggered at the time instant 156 seconds and it drops approximately to 1115 trajectories until 172 sec. The loss of maneuverable space for all three aircraft within these 16 seconds is significant. Another loss occurs at the time instant 400 seconds and decreases until the end of ecosystem time (430 sec) to 875 trajectories.



Figure 6 – Indicator 2 results for ecosystem 1

Figure 6 shows the number of solutions in time measured by Indicator 2. First thing that can be noticed is difference in the number of initial solutions. This can be justified by the different counting strategy of the 2 methods. The first one will count a maneuver on the left as unique solution, while the second will differentiate a solution that comes as a result of a 15° left maneuver from another one result of a 30° maneuver and count 2 distinctive solutions.

The second thing that can be seen is that the two curvatures are drastically different. Indicator 1 suggests for a simple ecosystem, where solutions are not fading quickly and therefore implies that agents can be more aggressive during the negotiations. Indicator 2 however suggests a sharper decrease rate which will call for a more collaborative negotiation between the agents.



Figure 7 - Indicator 3 results for ecosystem 1. Arc lengths of conflict aircraft 1, 2 and their sum

What indicator 3 suggests furthermore is that aircraft 2 has a wider clearance. This suggests that it will probably be easier to convince this agent to reach an agreement than the other agent.

B. Ecosystem 2





As can be seen from Figure 8, ecosystem 2 is composed of four aircraft. A conflict occurs between two aircraft in cruising configuration (red and black trajectories), with an overtaking scenario (loss of self-separation between two aircraft flying in the same direction). Figure 7 illustrates a rate of change in amount of the feasible trajectories over the time evolution, obtained at the time of triggering the ecosystem of approximately 6000. The rate, in this case, can be modeled as a step-wise function, with the smaller or greater quantity drops in discrete time intervals. It approached to zero value after 150 seconds of the ecosystem time.



Figure 9 - Indicator 1 results for ecosystem 2

Indicator 1 here has a small decreasing rate initially and then changes to a more drastic one. This will suggest an initial selfish approach for the agent and a later collaborative one.



Figure 10 - Indicator 2 results for ecosystem 2

Indicator 2 in this ecosystem counts less initial solutions than indicator 1. Moreover a similar shape is detected between the 2 curves.



Figure 11 - Indicator 3 results for ecosystem 1. Arc lengths of conflict aircraft 1, 2 and their sum

Indicator 3 here suggests similar amount of clearance for the two conflict aircraft which should be materialized in similar behavior of them.

5. CONCLUSIONS

This study particularly analyze the ecosystem complexity through three indicators and compares the provided results. All three indicators support preservation of the SM criteria, generation of the spatiotemporal interdependencies, and the ecosystem identification metrics by agreed maneuverability.

The first indicator produces the accumulative number of conflict-free system configurations over time. The second implements a greedy search process that counts for each path of the search tree only the conflict-free system configurations with minimal introduced perturbations. Considerably, the third indicator has been introduced to measure the accumulated length of the conflict-free arcs for all aircraft that have to perform a resolution maneuver.

Each indicator individually provides information. It can be seen from the results that in some cases drastically different behaviors can be suggested. This calls the necessity for further investigation of them to understand individual correlation to the actual complexity of a given ecosystem and further use in a multi-agent environment.

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