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GENERALIZED NET MODEL OF IN-QUEUE FLIGHTS

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Abstract. The paper presents a generalized net model of the process of situational optimization of in-queue flights. The latter are analyzed as discrete-event systems as they are influenced by different types of changes in the environment, which impose changes in the optimal flight parameters. The model is intended to say what actions should be undertaken at different deviations the discrete events cause. The generalized net model has seven transitions and five types of tokens.

I. INTRODUCTION

Air traffic management nowadays (especially on a European level) suffers many problems caused by lack of harmonization of national management systems, shortage in well trained specialized staff, airspace overload, ground operation overload, insufficient capacity of ground infrastructure, threads to security, etc. All these factors in turn lead to significant economic losses to airports and airway companies, constant flight delays, rush hours in hub airports, and decreased quality of the air traffic service. That provokes the search of innovative approaches to air traffic management and control. In-queue flights are one possible solution, and they have been a topic of research in the last 20-30 years. This concept envisages that a group of aircraft fly in a queue maintaining an altitude, speed and separation, and as well as that flight characteristics depend on the commands to the lead and the separation. Such an organization facilitates the work of air traffic control operators (ATCO) by distributing their attention to groups of ACs, instead of on single flights. In queue flights allow to delegate control functions to the flight deck, improve the quality of air traffic control and improve capacity use. The dynamics of these formations have so far being tested in simulation environment

Literature contains reports on multiple analyses and tests on whether a group of AC can execute such a flight. Analytical solutions for a two-AC queue via linear and nonlinear models are presented in [Bodner, 1975; Tarassov, 1980; Sorensen, Goka, 1983], however lacking reality in the description of the problem. The works [Cieplak, et al., 1994; Klass, 1996; Phillips, 1994] give detailed description of the phases of implementation of in-queue flights, although only radar-based separation is stressed. ADS-B-based (Automatic Dependent Surveillance – Broadcast) separation, as an alternative to radar separation is analyzed in [Ivanescu, et al., 2002; Hoffman, et al., 2002; Bevonious, Joseffson, 2002; Pritchett, Yankosky, 2003], which is a prerequisite to implement in-queue flights. Once feasibility of the formation is proven, optimality of the flight parameters (order, speed, flight level) at certain moments of the flight could be analyzed. Finding the optimal regime under undisturbed conditions is referred to as situational optimization of the queue. If safety considerations require changes in the regime, flight optimality becomes a secondary problem.

Thus, the optimal regime, being economic, should also allow changes in flight level and speed.

This paper focuses on the dynamic aspects of in-queue flights and the fact that once implemented those shall be affected by different kinds of changes in the environment. That is why it adopts the concept from [Dimitrakiev, et al., 2006] that in-queue flights can be perceived as discrete-event systems. A generalized net model is presented, which interprets the process of multiple implementation of the situational optimization procedure during the flight. The model has seven transitions and five tokens. In what follows, section 2 describes the discrete-event nature of in-queue flights, whereas the generalized net model in question is discussed in detail in section 3.

II. IN-QUEUE FLIGHTS AS DISCRETE-EVENT SYSTEMS

Feasibility of in-queue flights refers to the possibilities to combine aircrafts with different dynamic characteristics that are in position to maintain separation at a given altitude while following the lead. The work [Dimitrakiev, et al., 2006] proposed a procedure to find the optimal regime of an in-queue flight. For that purpose, they construct a hierarchical value function on parameters of control and safety, and elaborate an algorithm to find the flight regime where the value function is maximal. The entire procedure is called situational optimization of the in-queue flight. The optimal regime refers to a flight level and ordering of the aircraft (in descending order of minimal speeds for that flight level).

There are though other considerations to be taken into account, which refer to the dynamics of such formation once it becomes an element of air traffic. More precisely, this flight formation shall be subjected to multiple disturbances of different kind, such as landing, delays of aircraft, meteorological factors, emergencies, etc. These require changes in the flight regime of the queue, and in the individual flights (it must be kept in mind that a single flight might be analyzed as a queue consisting of a single aircraft) in order to retain stability and safety. Changes might be either structural (inclusion/exclusion of aircraft) or regime (changes in target speed, flight level, separation, masses, etc.). Following this, the work [Dimitrakiev, et al., 2006] suggested that in-queue flights should be analyzed as discrete-event systems [Ho, 1992; Samad, Weyrauch, 2000]. The authors argue there are four types of deviations caused by changes in the conditions (referred to as discrete events):

1) small deviations that do not affect the optimality of the flight, but impose changes in the structure of the value function; here it is possible to repeat the optimization within the possible operational limits of the AC without changing the structure of the queue;

2) medium deviations – such are deviations, which lead to non-optimal order within acceptable limits. Usually they are caused by including/excluding aircraft in the queue. In that case it is possible to have an old and a new part of the queue, as new aircrafts will be added at the back (at the tail) of the queue. These parts of the queue will be optimal, however, the connection between them may be unstable and the queue may split to several smaller queues;

3) substantial deviations that lead to unacceptably non-optimal ordering, i.e. the difference in minimal speeds of AC is too great to guarantee stability. This could be observed during changes of the flight level. Then the old part will not be optimally ordered, whereas the new part will be. Then again, an unstable connection between the old queue and its new tail will be present, as well as a necessity to split the queue into two new queues;

4) fatal deviations, which prohibit the in-queue flight. Such deviations are caused by technical failure in communication, runway problems, etc. The ATCO should then control each flight separately.

All these changes may occur at any time during the grouped flight, which is why the situational optimization should be used multiple times within a group flight depending on the number and type of discrete events. For that purpose [Dimitrakiev, et al., 2006] also proposes a structural scheme of the possibilities to use situational optimization in the control of in-queue flights. The scheme describes the activities to be taken if either of the four possible deviations occur. The easiest case is at small deviations, where it is only necessary to apply the optimization procedure once again. Medium deviations impose changes in the structure of the value function and partial restructuring of the queue. A decision module supports the action in the case of substantial deviations. Even if a solution is available there, it is likely that the queue will split into several queues and optimization shall be applied to each. Fatal deviations always obstruct the in-queue flight and impose independent flight regimes for each aircraft.

III. GENERALIZED NET INTERPRETATION OF IN-QUEUE FLIGHTS AS DISCRETE-EVENT SYSTEMS

In this section, the structural scheme of implementation of the situational optimization procedure from [Dimitrakiev, et al., 2006] shall be reconstructed as a generalized net model. The concept behind these is described in detail in [Atanassov, 1991]. These are perceived as extensions and modifications of Petri nets, which possess more and larger modeling possibilities. The properties and specific features of generalized nets are highlighted in detail in [Atanassov, 2001].

The generalized net that models the multiple application of the situational optimization procedure is depicted in fig. 1. It has seven transitions (Z_1, …, Z_7) and five types of tokens: $\alpha, \beta, \gamma, \delta, \varepsilon$. The tokens' places' and transitions' priorities are equal. The places and arcs capacities are infinite.

Tokens α enter the GN through place l_1 with initial characteristic

"aircraft parameters
(minimal and maximal flight level; minimal and maximal speed for each possible flight level; current mass; route)"

Below, each one of the α-tokens will be marked by α without indices.

Tokens β enter the GN through place l_2 with initial characteristic

"new discrete events"

Below, each one of the β-tokens will be marked by β without indices.

During all time of the GN functioning, tokens $\gamma, \delta, \varepsilon$ stay, respectively, in places l_6; l_{18} and l_{16} with initial and current characteristics:

"current result of the queues' structure"

"current ATCO's solution about the aircraft-queue association"

and

"current status of the archive"

They correspond, respectively, to the situation classificator, to the ATCO, and to the ATCO's archive.

$$Z_1 = <\{l_1, l_2, l_6\}, \{l_3, l_4, l_5, l_6\}, \begin{array}{c|cccc} & l_3 & l_4 & l_5 & l_6 \\ \hline l_1 & false & true & false & false \\ l_2 & false & false & false & true \\ l_6 & W_{6,3} & false & W_{6,5} & true \end{array} >,$$

where

$W_{6,3}$ = "there is new information for the ATCO",

$W_{6,5}$ = “there is a landing aircraft”.

Token α enters place l_4 with characteristics (see the discussion in section II):

“values of the deviation function for each queue classified as small, medium, substantial, and fatal”

Token β enters place l_6 and unites there with token γ. The later one obtains the mentioned above characteristic. When predicate $W_{6,3}$ is true, token γ splits to two tokens, the same token γ that continues to stay in place l_6 and token β' that enters place l_3 with a characteristic

“new information for the ATCO”

When predicate $W_{6,5}$ is true, token γ splits to two tokens, the same token γ that continues to stay in place l_6 and token γ' that enters place l_5 with a characteristic

“information for the current landing aircraft”

When both predicates $W_{6,3}$ and $W_{6,5}$ are true, token γ splits to the three tokens - γ, β' and γ', with the described above characteristics.

$$Z_2 = < \{l_4\}, \{l_7, l_8, l_9, l_{10}\}, \begin{array}{c|cccc} & l_7 & l_8 & l_9 & l_{10} \\ \hline l_4 & W_{4,7} & W_{4,8} & W_{4,9} & W_{4,10} \end{array} >,$$

where

$W_{4,7}$ = “the deviation is fatal”

$W_{4,8}$ = “the deviation is substantial”,

$W_{4,9}$ = “the deviation is medium”,

$W_{4,10}$ = “the deviation is small”.

Token α obtain the following characteristics:

“information for the ATCO imposing formation of queues containing single aircrafts”

in place l_7,

“additional information for the specific decision making problem regarding the queue structure”

in place l_8,

“determining the weight coefficients of the value function for the specific regime optimization problem”

in place l_9,

“solution for corrections of the queue structure”

in place l_{10}.

$$Z_3 =< \{l_8\}, \{l_{11}, l_{12}\}, \begin{array}{c|cc} & l_{11} & l_{12} \\ \hline l_8 & W_{8,11} & W_{8,12} \end{array} >,$$

where

$W_{8,11}$ = “there is a solution for corrections of the queue structure”,

$W_{8,12} = \neg W_{8,11}$

where $\neg P$ is the negation of predicate P.

Token α obtains the following characteristics:

“solution of the specific decision making problem for determining the aircraft-queue association”

in place l_{11},

“information for the ATCO imposing formation of queues containing single aircrafts”

in place l_{12}.

$$Z_4 =< \{l_9, l_{10}\}, \{l_{13}\}, \begin{array}{c|c} & l_{13} \\ \hline l_9 & true \\ l_{10} & true \end{array} >,$$

Token α obtains in place l_{13} the characteristic:

"results of the reoptimization procedure (flight level, target speed, and ordering of the new tails"

$$Z_5 = < \{l_{13}\}, \{l_{14}, l_{15}\}, \begin{array}{c|cc} & l_{14} & l_{15} \\ \hline l_{13} & W_{13,14} & true \end{array} >,$$

where

$W_{13,14}$ = "there is information for the ATCO".

If predicate $W_{13,14}$ has truth-value *true*, token α splits to two tokens - the same token α that obtains the characteristic

"current aircraft status (minimal and maximal flight level; minimal and maximal speed for the target flight level; current mass)"

in place l_{15} and token α' that obtains the characteristic

"information for the ATCO for the entire queue
(minimal and maximal flight level; minimal and maximal speed)"

in place l_{14}.

$$Z_6 =< \{l_3, l_7, l_{11}, l_{14}, l_{16}, l_{18}\}; \{l_{16}, l_{17}, l_{18}\}, \begin{array}{c|ccc} & l_{16} & l_{17} & l_{18} \\ \hline l_3 & true & false & true \\ l_7 & true & false & true \\ l_{11} & true & false & true \\ l_{14} & true & false & true \\ l_{16} & true & false & W_{16,18} \\ l_{18} & W_{18,16} & W_{18,17} & true \end{array} >,$$

where

$W_{16,18}$ = "there is request from the ATCO for old information from the archive",

$W_{18,16}$ = "there is information from the ATCO for the archive",

$W_{18,17}$ = "there is command from the ATCO for an aircraft".

The α-tokens from places l_3, l_7, l_{11}, l_{14} split to two equal tokens that enter places l_{16}, where they unite with token ε, staying permanently in this place with the above mentioned characteristic and l_{18}, where they unite with token δ, staying also permanently in this place with the above mentioned characteristic.

If there is necessity for information from the archive, token δ splits to two tokens - the same token δ and token δ'. The later one enters place l_{16}, unites with token ε that stays in this place and on the next time-moment token ε splits to two tokens - the same token ε and token ε' that enters place l_{18} with a characteristic

"the information necessity for the ATCO"

and unites there with token δ.

If there is necessity for commands from the ATCO to some or all airplans, token δ splits to two tokens - the same token δ and token ζ. The later one enters place l_{17} with a characteristic

"a command from the ATCO to the aircraft".

$$Z_7 = \langle \{l_5, l_{12}, l_{15}, l_{17}, l_{21}\}; \{l_{19}, l_{20}, l_{21}\}, \begin{array}{c|ccc} & l_{19} & l_{20} & l_{21} \\ \hline l_5 & true & false & false \\ l_{12} & false & false & true \\ l_{15} & false & false & true \\ l_{17} & W_{17,19} & W_{21,20} & W_{19,21} \\ l_{21} & W_{21,19} & W_{21,20} & W_{21,21} \end{array} \rangle,$$

where

$W_{17,19}$ = "there is command from the ATCO to the current landing aircraft",

$W_{17,20}$ = "there is command from the ATCO to the current flying aircraft whose status will be modified as a result of changes in the situation",

$W_{17,21}$ = "there is command from the ATCO to the current flying aircraft that status will be not modified on the present time-moment",

$W_{21,19}$ = "the current aircraft will land",

$W_{21,20}$ = "the current aircraft will modify its status as a result of changes in the situation",

$W_{21,21}$ = "the current aircraft will not modify its status".

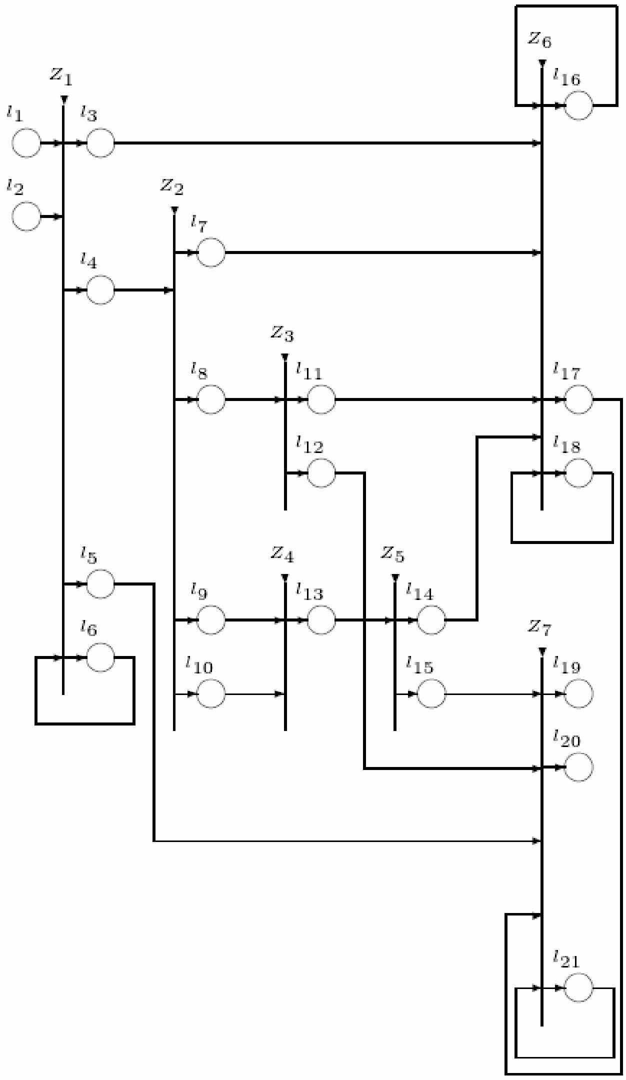

Fig. 1. Generalized net modeling the multiple use of situational optimization in flight control

The α-tokens from places l_5, l_{17}, and l_{21} entering place l_{19}, where they unite with β-token (if it exists and if it is related to the current α-token), obtain characteristic

"landing command to the aircrafts".

The α-tokens from place l_{21} entering place l_{20}, where they unite with β-token (if it exists and if it is related to the current α-token), obtain characteristic

"new flight regime for the aircraft".

The α-tokens from places l_{12}, l_{15}, and l_{21} entering place l_{21}, where they unite with β-token (if it exists and if it is related to the current α-token), obtain characteristic

"no command to the aircraft (status-quo)".

IV. CONCLUSION

The paper discussed the modern concept of in-queue flights as a way to effective flight control. Mentioned was a situational optimization procedure, which finds the optimal flight regime by maximizing a hierarchical value function. In queue flights were interpreted as discrete-event systems, influenced by discrete events (structural or regime). Those could cause four types of deviations, as a result of which situational optimization should be implemented multiple times. The generalized net model constructed includes seven transitions and five tokens. In future research, this model could be integrated and verified in an entire system to model the actual performance of in-queue flights.

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