OPTIMIZATION OF DISCRETE-EVENT DRIVEN IN-QUEUE-FLIGHTS

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Abstract: *In-queue flights are discussed in the paper, from the point of view of their situational optimization with respect to controllability and economy. The construction of an additive value function under strict certainty over the controllability and economy parameters is presented. Optimal flight parameters are defined by maximizing the value function over the multi-dimensional consequences. The focus is on the possibilities to apply situational optimization multiple times in the control of the queue, with respect to the occurrence of discrete events of different type. Schemes are developed to describe the process of optimization depending on the types of events and the required deviation from the current regime.*

Keywords: *in-queue flights, discrete-event dynamic systems, situational optimization*

1. INTRODUCTION

A modern trend in air traffic management is the in-queue formation, where flight characteristics depend on the commands to the lead and the separation. This is a possibility to facilitate the work of air traffic control operators (ATCO) by distributing their attention to groups of ACs, instead of on single flights. In this way control functions over the flight are given to pilots, the quality of air traffic control is improved and capacity of airspace is better exploited. Testing the feasibility and stability of such flight formations is done by computer simulation, as a flexible, reliable, fast and comparatively cheap way of analyzing the dynamic behavior of ACs in queue. Much research is conducted in the in-queue flight field, all aiming to test 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. Detailed description of the phases of implementation of in-queue flights is given in [Cieplak, et al., 1994; Klass, 1996; Phillips, 1994], although only radar-based separation is stressed. ADS-D-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.

In [Dimitrakiev, et al., 2006] a simulation platform in MATLAB 7.0 is presented to test the feasibility of in-queue flights. An important part of the system is the situational optimization of the queue, made with respect to economy and controllability of the flight. A multi-criteria decision problem is defined, and an additive value function is constructed over the chosen parameters under strict certainty. Maximization of the value function gives the optimal flight parameters in terms of speed, flight level and order of AC. The in-queue flight formation is influenced by the occurrence of discrete events of different character, as well by the commands of ground controllers. For this reason it can be viewed as a discrete-event system.

This paper discusses the possibilities for multiple application of the situational optimization procedure from [Dimitrakiev, et al. 2006] in cases when the in-queue flight system should react to discrete-event-driven changes in flight parameters. Procedures for optimization, reconstruction of the value function, change of flight parameter assignments and queue splits are discussed at different type of events. In what follows, section two discusses the provision of controllability and economy as a multi-criteria decision problem. Under strict certainty and mutual preferential independence of attributes, an additive value function is constructed over the controllability and economy parameters, and the optimal flight regime is defined by maximizing the value function over the consequences. Section 3 presents two schemes dealing with the possibilities for optimization of the queue due to different types of events and required deviations from the current regime, viewed as a discrete-event dynamic system. Section 4 presents simulations tests, which demonstrate the use of optimization in cases when the queue flight should adapt to changes caused by discrete events.

2. BUILDING AND OPTIMIZING AN ADDITIVE VALUE FUNCTION OVER FLIGHT REGIMES

In controlling the queue, ATCO are expected to assign permissible flight regime to the lead, i.e. ones that can be executed by all AC in the queue. Ordering AC in the queue is preferably handled in descending order of the minimal TAS (true air speed) of ACs. In such a way clashes can be avoided if extreme speed commands are assigned to the lead, and in the worst case scenario the formation may split up.

Situational optimization is performed at a moment, in which no transition processes occur, i.e. there are no discrete events. Furthermore, at the analyzed moment changes in target TAS, flight level, separation and masses do not take place. The queue formation process is also not considered. This process shall be performed whether an optimal or a non-optimal queue is created, and thus it does not influence the overall economic effect of the group flight. The optimization procedure may be used at two different stages of the in-queue flight. One stage is the process if initial queue formation, when all optimal parameters (TAS, flight level, order of AC) could be assigned and executed. Another stage is after occurrence of discrete events. Here, optimal speed and flight level commands could be defined, but order can be assigned only for the new part of the queue (if applicable), for reordering the old part would cause a serious violation of safety, which would not justify the optimality of the flight. Main considerations in the optimization are controllability by the ATCO and economy of the flight. Controllability by ATCO is possible through changes in flight level and TAS, whereas economy is considered from the point of view of fuel losses (related to the group flight, which does not allow each AC to operate on its optimal characteristics for minimal fuel loss).

Measuring controllability is handled by three parameters: $DTASdown$ – reserve for TAS reduction (at a certain flight level), being the difference between the target TAS and the minimal possible for the queue at this flight level; $DTASup$ – reserve for TAS increase, being the difference between the maximal possible TAS for the flight level and the target TAS; $DFLup$ – reserve for flight level increase, being the difference between the maximal possible and the actual flight level of the queue. Two parameters to measure economy are used: $FFa^{(k)}$ – absolute fuel loss by an AC, being the difference between the actual fuel flow for a certain TAS and flight level, and the minimal possible fuel flow (for k=1, 2, …, nac, where nac is the number of AC in the queue); $FFr^{(k)}$ – relative loss of fuel of an AC, being a ratio of $FFa^{(k)}$ and the minimal possible fuel flow. In that case, consequences from choosing TAS and flight level form a (3+2nac) – dimensional vector of consequences $\vec{\mathbf{x}}$:

$$\vec{\mathbf{x}}=\big(DTASdown, DTASup, DFLup, FFa^{(1)}, FFr^{(1)},\\ , FFa^{(2)}, FFr^{(2)}, ..., FFa^{(nac)}, FFr^{(nac)}\big)\,. \qquad (1)$$

As strict certainty is assumed (i.e. no uncertainties and risks are accounted in the optimization process), choosing between consequences defines the choice of an optimal flight regime. As proven in [Debreu, 1995; Pruzan, Jackson, 1963], mutual preferential independence is required to construct a value function of additive type over multi-dimensional prizes. Let's change all parameters at a time, but the k-th and (k+1)-th, both regimes being permissible. This operation shall not change the relative preference of the decision maker (DM) over the regimes, thus mutual preferential independence holds. On that grounds, an additive value function VF(.) over the coordinates of $\vec{\mathbf{x}}$ is constructed to describe the subjective preferences of the DM over all possible flight regimes:

$$VF(\vec{\mathbf{x}})=w_1(x_1)+w_2(x_2)+\ldots+w_{3+2nac}(x_{3+2nac}) \qquad (2)$$

$$w_i(x_i)=K_i V_i(x_i)\text{ , for } i=1,2,\ldots,3+2nac, \qquad (3)$$

where $V_i(x_i)$ is a normalized value function over the **i**-th parameter of $\vec{\mathbf{x}}$ (call?d parameter value function), whereas K_1, K_2, .., K_{3+2nac} are non-negative weight coefficients with sum normalized to one. Absolute and relative fuel loss are defined for each AC, thus $V_4(.)$, $V_6(.)$, ..., $V_{2nac+2}(.)$ are one and the same, denoted as $V_4(.)$, and the same holds for $V_5(.)$, $V_7(.)$, ..., $V_{2nac+3}(.)$, denoted as $V_5(.)$. Because of the strict certainty assumption, DM shall choose not between actions (i.e. 2-D vectors of speed and flight level to assign to the queue), but between (3+2nac) – dimensional vectors of consequence $\vec{\mathbf{x}}$. The most preferred consequence defines the necessary commands to the queue.

In modelling the parameter value functions it is assumed that preferences over each parameter increase with the increase ($?TASdown$, $?TASup$, $DFLup$) or decrease ($FFa^{(k)}$, $FFr^{(k)}$) of the parameter value, but it is of importance within certain intervals. Beyond these preferences are either 0 (parameter value not satisfactory) or 1 (parameter value satisfactory to assure controllability/economy). In between, preferences linearly increase with the increase/decrease of the parameter value. The appearance of the functions is presented on fig. 1 and 2. So stated, the parameter value functions are of fuzzy character, i.e. they can be interpreted as a degree of membership of the argument to the fuzzy set of acceptable parameters. Each DM may use arbitrary parameter value functions, but the optimal regime will only slightly differ from the one achieved here.

As (3) implies, the value of each parameter is weighted with the coefficients K_i. Since all K_i cannot be assessed directly, they are distributed into logical groups, with sum normalized to one. One group contains the coefficients for relative significance of controllability and economy (K_{man} and K_{FF}). A second groups contains coefficients for relative significance of TAS increase, decrease and flight level increase with respect to controllability ($K_{TASdown}$, K_{TASup} and K_{FLup}).

A third group contains coefficients for relative significance of each AC for the economy of the flight ($K_{AC}^{(1)}$, $K_{AC}^{(2)}$, ..., $K_{AC}^{(nac)}$). The last group consists of parameters for relative significance of absolute and relative fuel loss for each AC ($K_{FFa}^{(k)}$ and $K_{FFr}^{(k)}$, for k=1,2,…, nac). In that case $VF(\vec{\mathbf{x}})$ is calculated on the basis of 3+nac auxiliary value functions for controllability, fuel losses and economy, as follows:

$$VF_{man}=\\ =K_{TASdown}\times V_1(DTASdown)+K_{TASup}\times V_2(DTASup)+\\ +K_{FLup}\times V_3(DFLup)\,, \qquad (4)$$

$$VF_{AC}^{(k)} = VF_{AC}^{(k)}\left(FFa^{(k)}, FFr^{(k)}\right) = \\ = K_{FFa}^{(k)} \times V_4(FFa^{(k)}) + K_{FFr}^{(k)} \times V_5(FFr^{(k)}) \,, \quad (5)$$

$$VF_{FF} = VF_{FF}\left(VF_{AC}^{1}, VF_{AC}^{2}, ..., VF_{AC}^{(nac)}\right) = \\ = \sum_{k=1}^{nac}\left(K_{AC}^{(k)} \times VF_{AC}^{(k)}\right), \quad (6)$$

$$VF = VF\left(VF_{man}, VF_{FF}\right) = \\ = K_{man} \times VF_{man} + K_{FF} \times VF_{FF} \quad (7)$$

$$VF = VF(\bar{\mathbf{x}}) = K_{man} \times \left[K_{TASdown} \times V_1(?TASdown) + \\ + K_{TASup} \times V_2(?TASup) + K_{FLup} \times V_3(?FLup)\right] + \\ + K_{FF} \times \sum_{k=1}^{nac}\left\{K_{AC}^{(k)} \times \left[K_{FFa}^{(k)} \times V_4(FFa^{(k)}) + \\ + K_{FFr}^{(k)} \times V_5(FFr^{(k)})\right]\right\}, \quad (8)$$

where VF_{man} is the value function for controllability, $VF_{AC}^{(k)}$ is the value function for economy of each AC, and VF_{FF} is the value function for economy of the queue. On that basis, an algorithm is elaborated in [Dimitrakiev, et al. 2006] for situational optimization. Permissible command combinations are defined for the queue, and the optimal fuel loss, flight level and target TAS are calculated by maximizing $VF(.)$ on the permissible combinations. At a final stage, reordering of the queue is performed, in descending order of the minimal TAS for the optimal flight level.

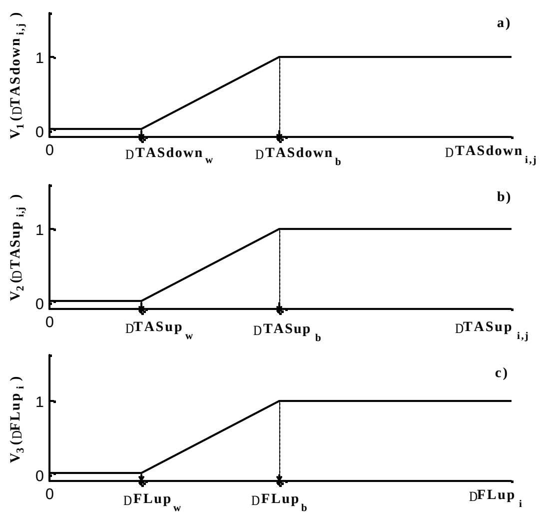

Fig. 1. Value function over the parameters for controllability of the queue

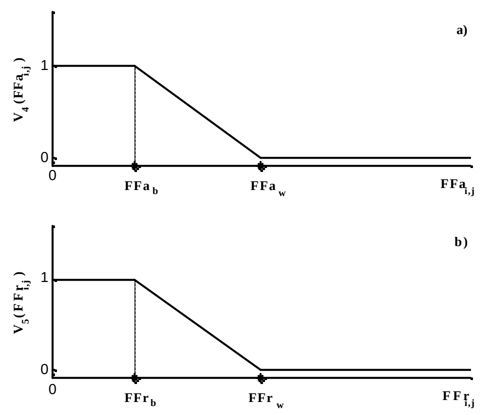

Fig. 2. Value functions over the parameters for economy

3. EVENT-DRIVEN NATURE OF IN-QUEUE FLIGHT SYSTEMS

The principle of discrete event dynamic systems [Ho, 1992; Samad, Weyrauch, 2000], as a method to control complex dynamic systems influenced by discrete events, is applicable to the control of in-queue flights. The latter are usually affected by regular or emergency events (see table 1). The latter require changes in the flight regime of the group flight and of the individual flights in order to retain stability and safety. Changing flight level, TAS and separation are the main possibilities to react to the changes. From the point of view ?f the flight these events may form two groups

1) Structural events, which cause inclusion or exclusion of AC;
2) Regime events, which cause changes in the target TAS, flight level, separation, masses of AC, etc.

A standard regime could be defined for each queue. Discrete events cause changes in that regime. For example, decrease of visibility requires from AC to gradually increase separation. This means that both the main regime of the queue, and individual TAS commands should be changed. If visibility returns to normal values, the queue will be at a regime, different from the standard one, which would again require group and individual commands to restore the standard parameters. Assuring stable transitions of such kind is a key precondition for safety of the flight.

Three types of possible deviations from the current regime of the queue could be expected:

Table 1. Types of discrete events influencing the queue

regular	**meteorological**	**emergency**	**catastrophic**
• landing • arrival of a new AC in the queue • delay of an AC • ...	• wind • temperature • visibility (fog) • snow • rain • ...	• runway problems - lights - jams - bus failure • unknown AC • birth nock • VIP – problem • Military mission • ...	• AC emergency • Diversion • Natural disaster - earthquake - ......

1) Small deviations – such are deviations, which change the structure of $VF(.)$, but retain the optimal order. 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, i.e. there are slight differences in minimal speeds of AC, so that there is still certain stability of the flights. In both cases, a new structure of the value function $VF(.)$ would be required over the parameters for controllability and economy. If an internal AC is excluded, the separation between ACs before and after the excluded AC is significant, which requires to assign individual TAS commands to compensate. The process may be executed automatically, as long as the flight management system of the AC could handle substantial deviations in parameters, without causing clashes. Medium deviations will also be present when adding new AC at the tail of the queue. If flight level remains the same, the old and the new part of the queue will fly in an optimal order, but the connection inbetween will be unstable. Optimal ordering will be only partially provided;
3) Substantial deviations – such are all deviations, leading to unacceptably non-optimal ordering, i.e. the difference in minimal speeds of AC is too high to guarantee stability. This could be observed during changes of the flight level. If a structural event occurs, e.g. new AC come into the queue, the old part of the queue will most probably be in a non-optimal order, whereas the new part will be optimally ordered. Partial optimality with an unstable connection within the queue will then be present. Controllers should be prepared to assign individual commands to AC or to split the queue into two or three new ones;
4) fatal deviations – those are caused by any events or actions (e.g. technical failure in communication, runway problems, etc.), which prohibit AC from flying in queue and require from controllers to guide each AC separately.

Situational optimization is a way to find optimal parameters under certain flight conditions and structure of the queue. Discrete events cause changes in the flight regime. That calls for new flight parameters, which could be again defined by the situational optimization procedure, i.e. it could be used multiple times within a group flight depending on the number and type of discrete events. A limitation of the process in that case would be that inclusion or exclusion of an AC would not lead to reordering of the queue, regardless of the operational characteristics of the AC. New combinations of flight level, TAS and separation will be only accepted and executed, otherwise safety of the flight is seriously violated. Structural scheme of the possibilities to use situational optimization in the control of an in-queue flight is presented on fig. 3.

Discrete events and ATCO commands require corrections in the flight regime. Small, medium, substantial, or fatal deviations may be needed depending on the type of event. At small deviations, the situational optimization procedure could be applied within the permissible operational and regime characteristics, without changing the ordering of AC in the queue. Medium deviations would cause changes in the structure of the value function over the queue. Optimization could be performed after that, but new ordering would be accepted only for the new part of the queue (if such). At substantial deviations, possibilities could be searched in the decision module. Even if such are found, ordering of the queue would not be optimal and the connection between the old and new part of the queue would be unstable, and a split into *n* number of new queues would be needed. For each, a new value function must be established, and situational optimization should be performed to define optimal TAS, separation and flight level, without changing the order of AC. In case an alternative is not found in the decision module, decision should be found by the ATCO. The same occurs at fatal deviations, when it is not possible to apply standard control schemes and direct ATCO commands are needed so that not to violate safety of the flight. In most cases, that means discontinuing of the group flight and individual control of each flight. Data from the information system and its intelligent filtration by decision support systems assists the ATCO in her/his decisions.

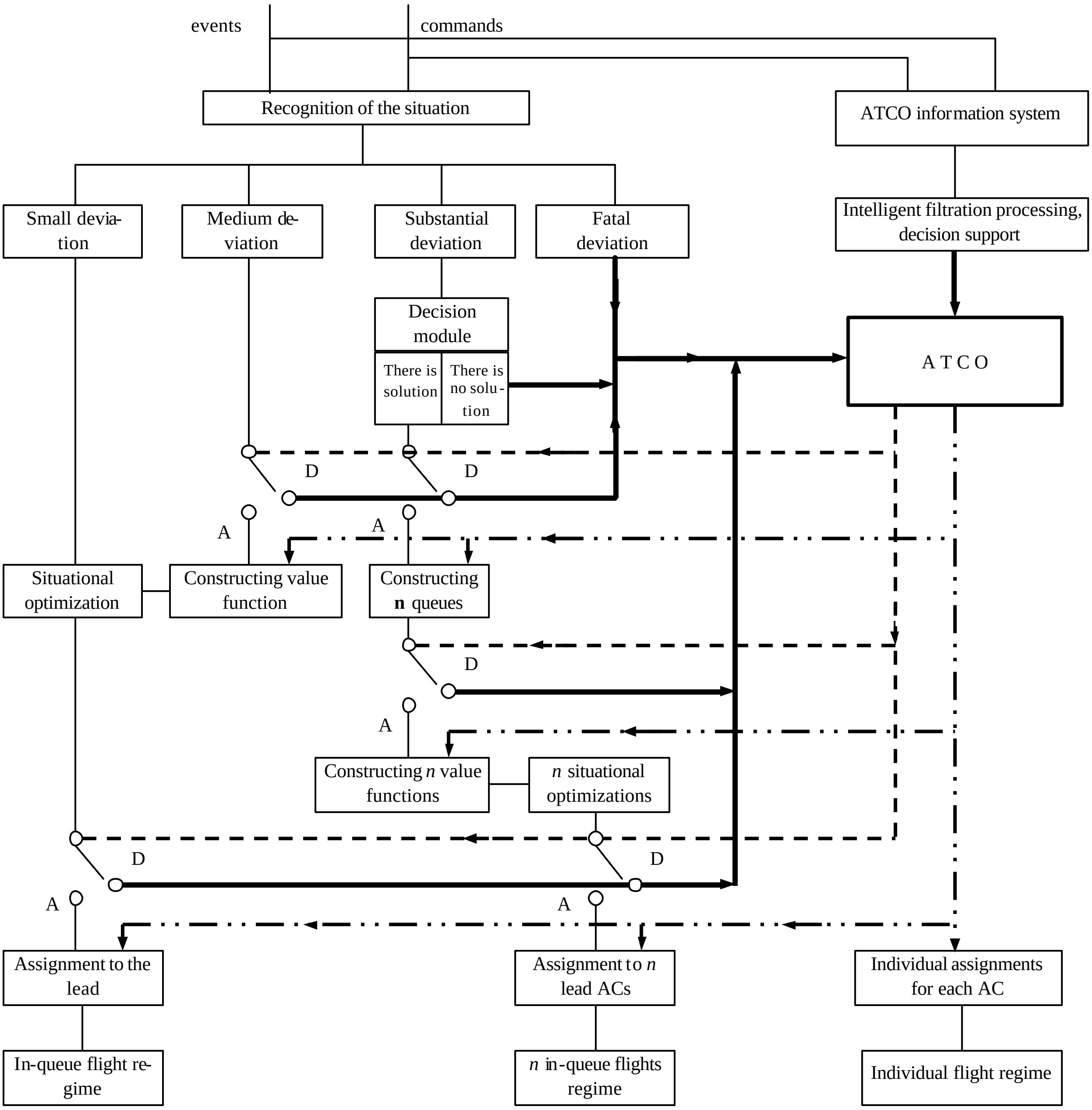

Fig. 3. Scheme of the use of situational optimization in flight control

The controller may decide whether different control stages of the discrete-event system should be executed automatically or by her/him. ATCO may assign the tasks of building the value function, changing/creation of queue, or ways to split an old queue into several new to herself/himself. Assigning commands to the lead could also be tasked to the automated control system. The ATCO cannot be replaced only in the definition of individual commands to the AC after substantial or fatal deviations and termination of the group flight.

Situational optimization could also be used on-line to control AC in a manual and automatic regime, as shown on fig. 4.

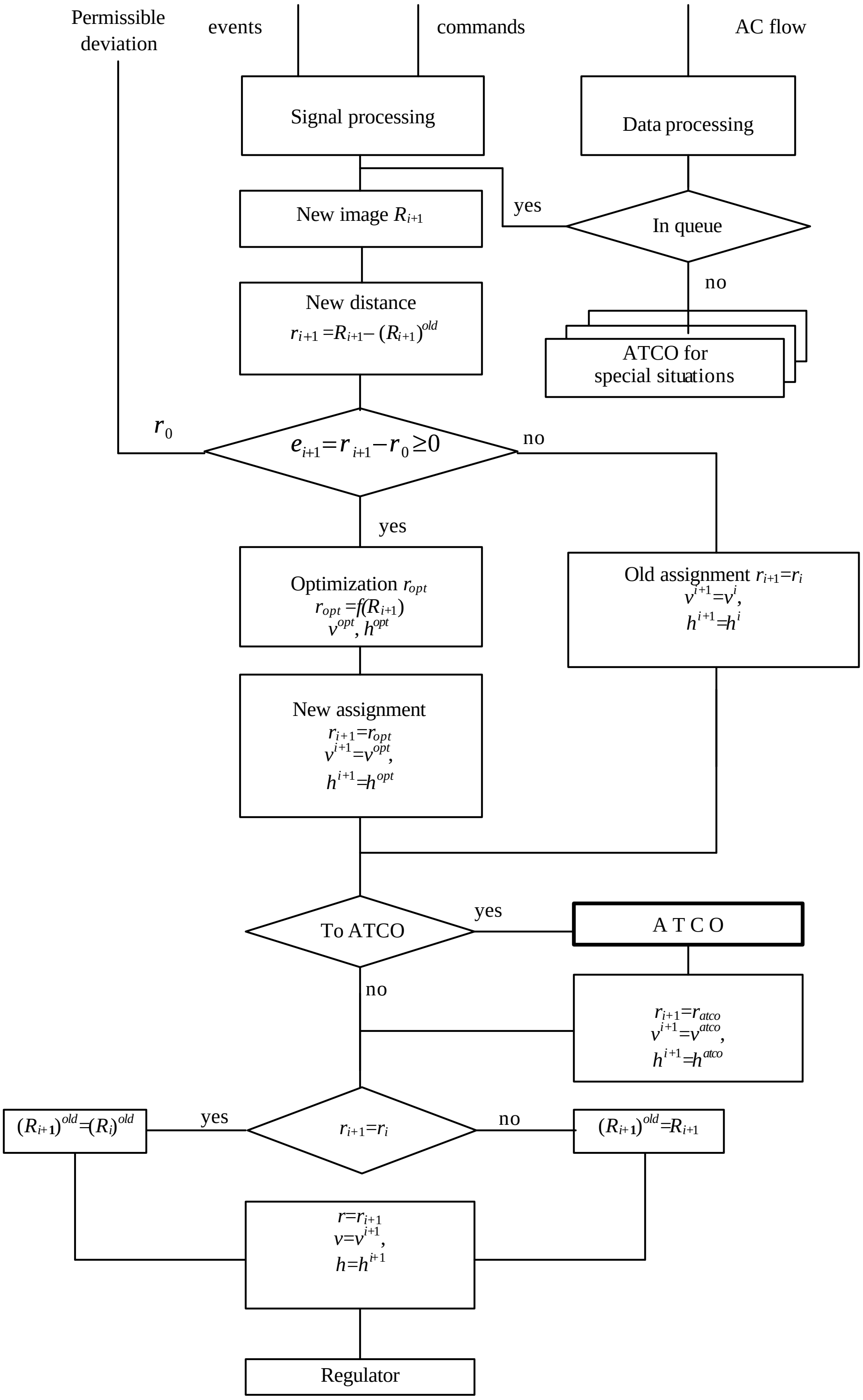

Fig. 4. Scheme of assignment change for the in-queue flight because of discrete events

New images of the flight (in terms of speed and flight level) are defined on the basis of discrete events and ATCO commands. Analyzed is also the traffic in the region with respect to the inclusion of new AC. Control procedures are applied to define the fitness of the AC for the queue. If such is established, the AC may be included in the queue, otherwise it is assigned to an individual controller.

The difference between the new R_{i+1} and the current value of the old $(R_{i+1})^{old}$ image of the flight is a measure for the distance (r_{i+1}) of the current from desired state of the queue. Let r_0 denotes the permissible deviation from the flight parameters, at which change in the regime is not required. If the calculated distance to the desired image exceeds r_0, new optimization is needed to find a new optimal regime r_{opt} (of speed v^{opt} and flight level h^{opt}), as a function of the desired flight regime. On that basis new assignments to the queue $r_{i+1}=r_{opt}$ are defined, where $v^{i+1}=v^{opt}$ and $h^{i+1}=h^{opt}$. If the distance does not exceed r_0, then old commands apply, i.e. $r_{i+1}=r_i$ ($v^{i+1}=v^i$, $h^{i+1}=h^i$).

In assigning new commands by the ATCO, a new control set is formed $r_{i+1}=r_{atco}$ ($v^{i+1}=v^{atco}$, $h^{i+1}=h^{atco}$). If assigning commands to the lead is to be automatically performed, then r_{i+1} transforms into assignment for automatic control from the regulator $r=r_{i+1}$, where $v=v^{i+1}, h=h^{i+1}$. To guarantee proper operation of the scheme, an identity check is performed over the new and the last executed commands, i.e. whether $r_{i+1}=r_i$. If the condition does not hold, the new image R_{i+1} is recorded as the current value of the old image, i.e. $(R_{i+1})^{old}=R_{i+1}$. Otherwise, the current value of the old image coincides with the former one, i.e. $(R_{i+1})^{old}=(R_i)^{old}$.

4. SIMULATION TESTS

The control procedures over a queue with respect to discrete events, discussed above, shall be demonstrated through tests in the simulation platform presented in [Dimitrakiev, et al., 2006]. Let's test a queue of five ACs as follows: A320, A306, B752, A30B, B744 (*nac*=5). The payload at takeoff of the AC is respectively 17100 *kg*, 43350 *kg*, 28198 *kg*, 17392 *kg*, and 3682 *kg*, whereas the fuel at simulation start is respectively 15200 *kg*, 24750 *kg*, 20280 *kg*, 18848 *kg*, and 55520 *kg*. The value function *VF* is constructed over the queue, with the following parameters (following (8)):

weight coefficient:
$K_{man}=0.4$, $K_{TASdown}=0.3$, $K_{TASup}=0.3$,
$K_{FLup}=0.4$, $K_{FF}=0.6$, $K_{AC}^{(1)}=0.3$, $K_{AC}^{(2)}=0.2$,
$K_{AC}^{(3)}=0.2$, $K_{AC}^{(4)}=0.1$, $K_{AC}^{(5)}=0.2$, $K_{FFa}^{(1)}=0.7$,
$K_{FFa}^{(2)}=0.6$, $K_{FFa}^{(3)}=0.4$, $K_{FFa}^{(4)}=0.7$, $K_{FFa}^{(5)}=0.4$,
$K_{FFr}^{(1)}=0.3$, $K_{FFr}^{(2)}=0.4$, $K_{FFr}^{(3)}=0.6$, $K_{FFr}^{(4)}=0.3$,
$K_{FFr}^{(5)}=0.6$.

Margins for the parameter value functions:
$DTASdown_w=1kts$, $DTASdown_b=10kts$,
$DTASup_w=1kts$, $DTASup_b=8kts$, $DFLup_w=2$ (100*ft*), $DFLup_b=7$(100*ft*), $FFa_b=0.4kg/nm$,
$FFa_w=0.9kg/nm$, $FFr_b=0.55\%$, $FFr_w=11\%$.

Steps:
step_FL=2 (100 *ft*), *step_vtarg*=2 *kts*.

The parameters *step_FL* and *step_vtarg* define the grid of possible flight regimes (of speed and altitude) between which the optimal one is searched for. The lower the values of those parameters the more precise the optimization is since it is performed on a greater amount of possible combinations. Different fuel flow weight coefficients for the AC (K_{AC}) account for the fact that each is of different significance for the controller. This may be due to previous bad performance of AC, priority considerations for some airliner, etc.

Optimization is performed, and it recommends target TAS of 460 *kts* and flight level of 326 (100*ft*). The optimal order of AC should be A306, B744, A30B, B752, A320. At those parameters it is calculated that the AC in the queue will use up a total of 50.19 *kg/nm* of fuel, and the speed may vary between 432 *kts* and 482 *kts*, whereas the maximal possible flight level is 334 (100 *ft*).

The queue is driven for 40 *min* set at its optimal parameters (order, flight level, target TAS, as defined above). The TAS command to the lead decreases from the target TAS of 460 *kts* to 434 *kts* at the first minute of simulation, and at the tenth returns back to the target level and is kept at it till the end of the simulation (the TAS command to the lead can be changed during simulation, but only for future moments of simulation time). The graphical output, i.e. TAS of AC and separation maintained during the simulation are presented on fig. 5 and 6.

A small deviation from the regime occurs, caused by the continuous change of masses of the AC (due to decreased fuel), which affects their flight envelope. Fuel now available on the AC in the queue A306, B744, A30B, B752, A320 dropped respectively to 20636 *kg*, 52665 *kg*, 14877 *kg*, 17493 *kg*, and 13410 *kg*. As well as that weather conditions worsen and temperature decreases to -5^{0}C deviation from ISA. The parameters of the value function, considering the type of event, need not be changed. Optimization is again performed, which recommends target TAS of 446 *kts* and flight level of 336 (100*ft*). The optimal order of AC is not affected. At those parameters the AC in the queue will use up a total of 48.79 *kg/nm* of fuel, the speed may vary between 429 *kts* and 471 *kts*, whereas the maximal possible flight level is 344 (100 *ft*).

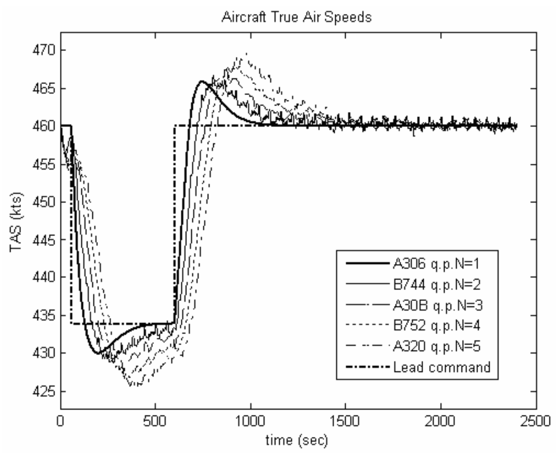

Fig. 5. TAS of each AC during the simulation

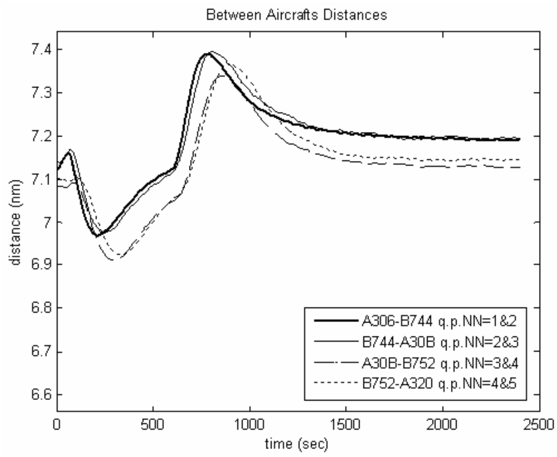

Fig. 6. Separation between AC during the simulation

After 20 *min* of flight under the new conditions, a discrete event occurs, which causes average deviation from the current regime. In particular, it is required to take A306, A30B, and B752 out of the queue, and add ?733, ? 319, ? 343, ?735 at the tail. Then the structure of the new queue should be B744, A320, ?733, ?319, ?343 and ?735. The payload of the new group of AC is respectively 3682 *kg*, 17100 *kg*, 11603 *kg*, 750 *kg*, 7700 *kg*, and 2082 *kg*, whereas their fuel at simulation start is respectively 51289 *kg*, 12541 *kg*, 12025 *kg*, 7600 *kg*, 104160 *kg*, and 7400 *kg*. The value function is affected from the change, and because of the bad weather conditions controllability receives greater importance. The relative importance of the old AC (B744 and A320) with respect to economy, defined before by the coefficients $K_{AC}^{(5)}=0.2$ and $K_{AC}^{(1)}=0.3$ (the positions of the AC in the initial queue were respectively 5 and 1), remain the same. In accordance to the lead and second position of the two AC in the new queue, the respective values are now assigned to coefficients $K_{AC}^{(1)}$ and $K_{AC}^{(2)}$. The step parameters *step_FL* and *step_vtarg* do not change:

weight coefficient:
$K_{man}=0.6,\ K_{TASdown}=0.3,\ K_{TASup}=0.2,$
$K_{FLup}=0.5,\ K_{FF}=0.4,\ K_{AC}^{(1)}=0.2,\ K_{AC}^{(2)}=0.3,$
$K_{AC}^{(3)}=0.1,\ K_{AC}^{(4)}=0.2,\ K_{AC}^{(5)}=0.1,\ K_{AC}^{(6)}=0.1,$
$K_{FFa}^{(1)}=0.6,\ K_{FFa}^{(2)}=0.4,\ K_{FFa}^{(3)}=0.4,\ K_{FFa}^{(4)}=0.45,$
$K_{FFa}^{(5)}=0.35,\ K_{FFa}^{(6)}=0.55, K_{FFr}^{(1)}=0.4,\ K_{FFr}^{(2)}=0.6,$
$K_{FFr}^{(3)}=0.6,\ K_{FFr}^{(4)}=0.55,\ K_{FFr}^{(5)}=0.65,\ K_{FFr}^{(6)}=0.45.$
Margins for the parameter value functions:
$DTASdown_w=1kts,\ DTASdown_b=10kts,$
$DTASup_w=1kts,\ DTASup_b=8kts,\ DFLup_w=2$ (100*ft*), $DFLup_b=7$(100*ft*), $FFa_b=0.4kg/nm,$
$FFa_w=0.9kg/nm,\ FFr_b=0.55\%,\ FFr_w=11\%.$
Steps:
step_FL=2 (100 *ft*), *step_vtarg*=2 *kts*.

Optimization is performed to find the best flight regime. The proposed parameters are: optimal target TAS 442 *kts*, optimal flight level 335 (100 *ft*), optimal order of the queue ? 343, ?744, ?733, A320, ? 735, ? 319. Of course, the old part of the queue (?744, ? 320) cannot be reordered, since that threatens safety of the flight. That is why the simulation platform structures ? partially optimal queue in the form ?744, ?320, ?343, ?733, ?735 and ?319. At those parameters the AC in the queue will use up a total of 45.37 *kg/nm* of fuel, the speed may vary between 431 *kts* and 471 *kts*, whereas the maximal flight level would be 343 (100 *ft*).

Simulation is performed for 80 *min*. Graphics of TAS and separation between ACs are produced, in the same fashion as those in fig. 5 and 6. At the first minutes of simulation the second AC is far away from the lead. This is due to the fact that two AC were taken off this section of the queue during restructuring. At the end of the experiment the flight management system of the second AC managed to establish normal (target) separation, constantly adjusting its speed in accordance to the current separation. The other four AC followed the second while maintaining proper separation.

5. CONCLUSIONS

The paper discussed problems related to in-queue flights. An approach to the optimization of such with respect to controllability and economy was discussed. For that purpose a hierarchical value function was created of parameter value functions and weight coefficients. Maximizing the value function is the way to find the optimal flight regime in terms of target TAS and flight level.

The comments made here show that the procedures for situational optimization may be applied multiple times to control the queue, when due to different discrete events it is necessary to define again the appropriate parameters of the flight. On that basis it is possible to construct a whole system for in-queue flight control, treated as a discrete-event system.

An intelligent part of the scheme could be developed through logical knowledge-based procedures, embedded into the system. The necessary data can be collected after a long term use of optimization procedures. This will additionally facilitate the work of controllers, and provide both group and individual decision support in different situations.

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