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Risk Analysis and Setting Priorities in Air Traffic Control by Using a Matrix of Similarities

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***Abstract* – This article considers how mathematical decision-making in Air Traffic Control could be done in order to minimize the risk of collisions. An example of how to prioritize airplanes which are in the vicinity of an airport according to their level of risk in respect to other airplanes is given by using a matrix of similarities and Euclidean metric. The analysis has shown that it is necessary to classify ATC specialists and ATC centers according to their ability to provide safe enough service using time methods and highly experienced team work.**

***Keywords* – Air traffic control, Euclidean metric, matrix of similarities, risk analysis.**

I. INTRODUCTION

Air traffic control (ATC) service is a service provided for the purpose of preventing collisions between aircraft and, on the maneuvering area, between aircraft and obstructions, as well as for the purpose of expediting and maintaining an orderly flow of air traffic. [1] In busy traffic environment it is necessary to make timely and accurate decisions which would guarantee the necessary level of safety, because the time of decision making for air traffic control officers (ATCOs) is limited. [2]

Nowadays technological development has changed the daily work of ATC centers rather noticeably relieving ATCOs from monotonous and repeated actions. Modern ATC work is more related to operations and management of technologically and functionally complicated electronic systems as the greatest part of all control functions are done automatically or semi-automatically. [3] For this reason, it is possible to discuss and evaluate the whole ATC work as a combination of many separate control systems where the main task is to receive, evaluate and analyze all available information in order to make right decisions. [4]

During flight an aircraft can get into various situation state and difficulties to which ATCO should react. Generally speaking, a complicated situation can be described as a condition and availability of a scheme "ATCO – crew – environment". [5] There are five basic states of this system:

1. Normal conditions or normal operation state of an aircraft;
2. Difficult flight conditions – a situation within which the physical and emotional condition of ATCO is a slightly higher than normal or within which the parameters of an aircraft during flight insignificantly fall below the requirements stated. In this case it is not necessary to divert the airplane from its intended path as it is still possible for the crew to fly via flight planned route 2.];
3. Complicated situation – a situation when special assistance is required where both – ATC and the crew – need additional psychological load and stability and handling of an airplane can deteriorate significantly. In this case the level of risk does not fall below requirements. To avoid any aviation accidents or incidents a timely and precise action from ATC and the crew is needed;
4. Aviation incident – an extraordinary situation when the psychological load of ATC and the crew rises significantly or when the handling of an airplane or other flight parameters deteriorate significantly;
5. Aviation accident – a situation when a person is fatally or seriously injured, the aircraft sustains damage or structural failure or the aircraft is missing or is completely inaccessible. [6]

The designation of such situations shows that the difference between all kinds of situations is not clear. It also shows that decision making in every situation is rather subjective and it strongly

depends on air traffic controller's situational awareness. [7] It is also rather difficult for him/her to decide which group each situation refers to, because it is rather impossible to define the limits between them. It is so, because each group is described using subjective characteristics, such as "significant – insignificant" and "possible – impossible". [8] For this reason, ATCOs are experiencing difficulties in handling unusual situations while on duty as there are no two equal unusual situations – each of them requires special assistance with special strategies and decisions.

II. General Regulations

The previous discussion can be illustrated graphically (see Fig. 1) [10]. Axis *X* represents the state of the whole system and axis *Y* represents the controller's view about the situation. Ideally ATCO will evaluate the situation correctly, without making any mistakes. For this reason, in the picture there is a 45° angle between the curve and axes ($\alpha = 45°$). In reality ATCOs can make mistakes. That is why the real and not the ideal curve may drift from ideal axis. Consequently, the angle will be less than 45° ($\alpha < 45°$).

As an example let us assume that an aviation accident has happened. ATCO has evaluated it as a complicated situation and not an accident because of insufficient or incorrect information. In this case to correct the mistake it is necessary to change the decision. [9] Graphically it is necessary to move downward along the curve until reaching point 2 where ATCO's decision does not match with the real situation. This process needs additional time and energy to gather and process additional information. After this ATCO needs to go back to the starting point and evaluate the situation once again taking into account the new information. It means that if the situation was evaluated incorrectly, it is necessary to go along the curve from point 1 to point 2, then to go back to the starting point, do the evaluation for a second time and only then develop a strategy to minimize the risk. The last action is graphically shown as a movement to the point 3.

This paper provides a way or method of calculating the level of risk in a busy traffic environment and its main goal is to help ATCO in setting correct priorities for ATC service provision. [11]

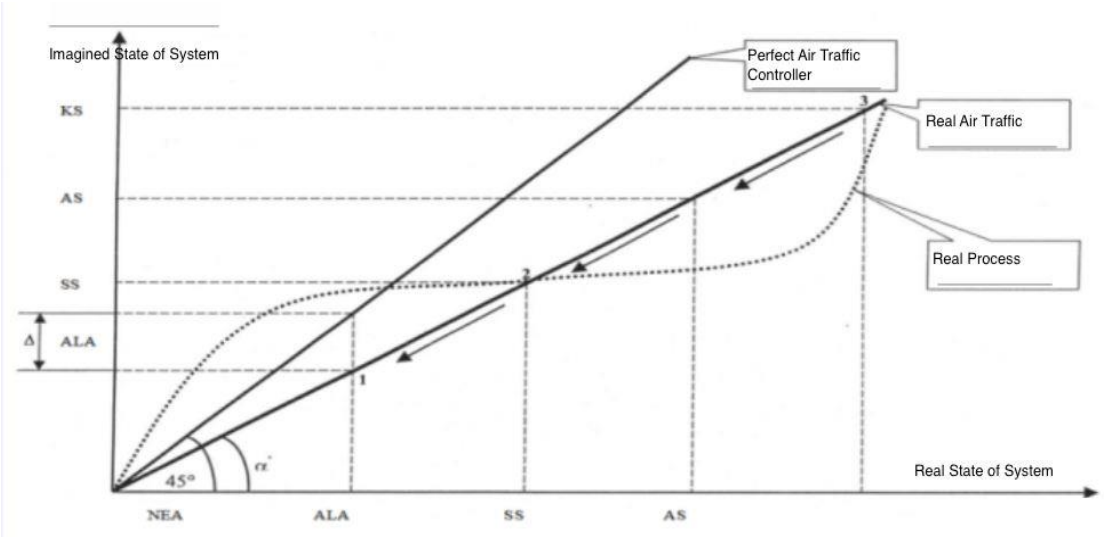

Fig. 1. Decision making process of an air traffic controller in complicated situations.

III. Calculation of Risk Level

There are different international, regional and local standards on ATC which describe which cases can be considered as safe and which cannot. The evaluation of conflict situation is based on clearly stated criteria. The main source for this information is ICAO's ATM-PANS "Doc 4444" stating

which separation must be used between aircraft in horizontal and vertical plane taking into account the classification of airspace and phases of flight. [12]

The analysis of Approach (APP) and Tower (TWR) controller's work shows that by evaluating the situation in each ATC sector the controller divides complex parameters into two groups: conflicting pairs of aircraft and not conflicting ones. Using these assumed similarities or coincidences between aircraft and representing vectors there is a task for ATC to put all aircraft into one sequence by taking into account the level of risk of each aircraft. This article considers how the evaluation could be done. The whole process can be divided into several parts:

1. Establishment of the matrix of similarities by taking into account angles between two vectors which represent airplanes and calculating cosine, scalar multiplication, distances between these vectors, etc.;
2. Comparison of matrix data with officially stated minimum separation values;
3. Determination of objects and pairs of objects which are likely to exceed these minima. [13]

The matrix of similarities is a symmetric square, and its elements, which are located on its diagonal, are equal and have the greatest value. The values of this matrix are calculated using coding of binary vectors. [14] In this work Euclidean metric is used to compare the values as well as the following measures of similarities (1), (2):

$$cos(X,Y) = \frac{(X*Y)}{\|X\|*\|Y\|} \tag{1}$$

$$\| X - Y \| = \sqrt{|X-Y| * |X-Y|} = \sqrt{\| X \|^2 + \| Y \|^2 - 2(X*Y)} \tag{2}$$

where $\boldsymbol{X}$ and $\boldsymbol{Y}$ – binary vectors inside the n-dimensional space of associated characteristics. Then (3):

$$\| X \| = \sqrt{(X*X)}, \| Y \| = \sqrt{(Y*Y)} \tag{3}$$

The amount of aircraft reaching the necessary safety requirements is determined by using the permissible values of the stated measures of similarities. Generally, such requirement must fulfill (see Fig. 2) (4):

$$max\, cos(X,Y)\, min \| X - Y \| \tag{4}$$

or there are some permissible values $_1$ and $_2$ (5).

$$\cos(X,Y) \gg \lambda_1 \ \| X - Y \| A = \ll \lambda_2 \tag{5}$$

Search algorithm can be simplified if such conditions arise (6):

$$\| X \| * \| Y \| = cons \| X \|^2 * \| Y \|^2 = const \tag{6}$$

Which are correct if (7):

$$\| X \| = \| Y \| = C(n) \tag{7}$$

where $C(n)$ – constant which depends only on the size of the room.

Equation (7) determines a point which is located at the same distance $C(n)$ measuring from the starting point of the axes, geometrical position or hyper sphere within n-dimensional space.

Conditions (4) and (5) lead to more simple algorithms (8):

$$\| X \| = \| Y \| = C(n) \geq \lambda_3 \tag{8}$$

where (9):

$$\lambda_3 = \lambda_1 C^2(n) = \sqrt{C^2 n - \frac{\lambda_1^{\frac{2}{2}}}{2}} \tag{9}$$

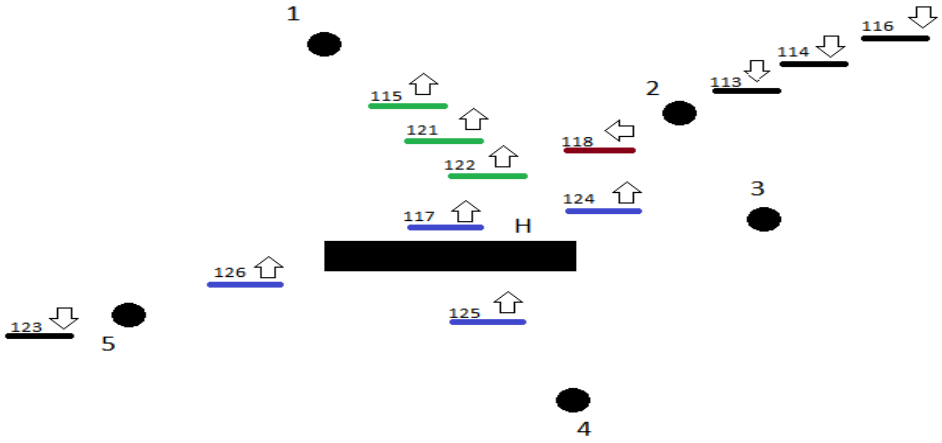

Fig. 2. Location of airplanes in the vicinity of airport H, as described in the example.

IV. Analysis of Situation

Let us have a look at one example of calculation of the level of risk. The situation (see Fig. 2) is taken from an airport H, and in peak hours there are approximately 12 airplanes in the vicinity of the airport. Runway heading at this airport can be either 090 or 270 degrees depending on wind direction, but in this example it is assumed that during this period of time runway 09 was in use.

Airplanes 113, 114 and 116, which are descending for landing at the airport H, are going inbound the waypoint PHT-2 (see Fig. 2) Speed control is applied for these airplanes so that they are not conflicting with each other.

Airplane 118 is a small private aircraft flying through the sector at constant altitude from waypoint PHT-2 to waypoint PHT-5 at a rather low speed.

Airplanes 117, 124, 125 and 126, which have departed from the airport H, are flying in the direction inbound PHT-1, PHT-3, PHT-4 and PHT-5 respectively.

Airplanes 115, 121 and 122 have also departed from the airport H and are gaining altitude inbound the waypoint PHT-1. Here it is also assumed that the speed of these three airplanes is higher than for airplane 117, which means that they are not conflicting.

According to the task and situation in the air there are two conflicting pairs of airplanes which make the decision-making more difficult. These pairs are airplanes 113–122 and 118–124. 113–122 are conflicting because 122 is gaining altitude at a lower speed and 122 is approaching the runway at high speed, which is appropriate to this type of aircraft. Airplanes 118 and 124 are conflicting because 118 is flying through the sector at a constant altitude at a rather low speed but 124 is climbing through its level. [15]

And now the task of the air traffic controller is to satisfy the needs of all the involved airplanes and meet the three main requirements:

1. Maintaining appropriate level of safety at all times;
2. So that airplanes, which intend to land at the airport H, would spend the least time in holding patterns;
3. So that airplanes, which are gaining altitude and have departed from the airport H, would spend the least time at low altitudes for the safety and fuel economy purposes. [16]

TABLE I

EVALUATION OF DESCRIBED SITUATION IN RESPECT TO 24 FACTORS WHICH MIGHT AFFECT THE LEVEL OF RISK

	AIRCRAFT											
NO.	113	114	115	116	117	118	121	122	123	124	125	126
1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	0	1	1	0	1	1	1
3	1	1	1	1	1	1	1	1	1	1	1	1
4	1	0	1	0	1	1	1	1	1	1	1	1
5	1	1	1	0	1	1	1	1	0	1	1	1
6	0	0	0	0	0	0	0	0	0	0	0	0
7	1	1	1	1	1	1	1	1	1	1	1	1
8	1	1	1	0	1	1	1	1	0	1	1	1
9	1	1	1	1	1	0	1	1	0	1	1	1
10	1	1	1	1	1	0	1	1	0	1	1	1
11	1	1	1	1	1	0	1	1	0	1	1	1
12	1	0	1	0	1	1	1	1	1	1	1	1
13	1	1	1	0	1	1	1	1	0	1	1	1
14	1	1	0	1	0	0	0	0	0	0	0	0
15	1	1	0	1	0	0	0	0	0	0	0	0
16	0	0	1	0	1	1	1	1	1	1	1	1
17	1	1	0	1	0	0	0	0	0	0	0	0
18	1	1	1	1	1	1	1	1	1	1	1	1
19	1	1	0	1	0	0	0	0	0	0	0	0
20	0	1	1	1	1	0	1	0	1	0	1	1
21	1	1	1	1	1	1	1	1	1	1	1	1
22	1	1	1	1	0	1	1	1	0	1	1	1
23	1	1	1	1	1	1	1	1	1	1	1	1
24	1	1	1	1	1	1	1	1	1	1	1	1

In such an intense environment the effectiveness of ATC work strongly depends on the priorities set. It means that it is vital to set priorities in respect to the requirements and measurements which determine the core of what a “safe situation” in ATC means. [7]

In order to evaluate the risk, Table I will be filled taking into account all the factors and their values which can affect the level of risk in the situation described above (see Table I). If the condition is evaluated as safe enough, in the table it is shown as 1, and if it is described as dangerous, it is shown as 0.24 different factors have been evaluated using this method.

It was assumed that the air traffic was observed for 10 minutes. This 10 minutes interval at the airport H is shown in the matrix of similarities in Table II.

Then it is necessary to find scalar multiplications and limits for each pair of vectors. For instance, for airplanes 113 and 114 it is (2), (4):

$$d(113, 114) = 3$$

$$(113*114) = n - d(113,114) = 24 - 3 = 21$$

$$\|113\| = 21, \ \|114\| = 20$$

The next step is to fill in the similarity matrix with values cos(*x*,*y*). These values are represented in Table III.

TABLE II

MATRIX OF SIMILARITIES FOR THE DESCRIBED SITUATION AT THE AIRPORT H

	d(*x*,*y*)											
NO.	113	114	115	116	117	118	121	122	123	124	125	126
113	0	3	5	5	7	9	6	5	14	5	6	6
114		0	6	3	8	12	7	8	15	8	7	7
115			0	10	1	5	0	1	8	1	0	0
116				0	11	15	10	11	12	11	10	10
117					0	6	1	2	7	2	1	1
118						0	5	4	5	4	5	5
121							0	8	8	1	0	0
122								0	9	0	1	1
123									0	9	8	8
124										0	1	1
125											0	0
126												0

TABLE III

MATRIX OF SIMILARITIES CALCULATING COS(*X*,*Y*)

	cos(*x*,*y*)											
NO.	113	114	115	116	117	118	121	122	123	124	125	126
113		0.0500	0.0480	0.0530	0.0450	0.0510	0.0450	0.0505	0.0430	0.0505	0.0450	0.0450
114			0.0474	0.0620	0.0445	0.0428	0.0445	0.0445	0.0410	0.0445	0.0446	0.0446
115				0.0431	0.0670	0.0715	0.0660	0.0670	0.0765	0.0670	0.0660	0.0660
116					0.0425	0.0380	0.0435	0.0425	0.0640	0.0425	0.0435	0.0435
117						0.0715	0.0675	0.0680	0.0860	0.0680	0.0675	0.0675
118							0.0175	0.0790	0.1240	0.0790	0.0715	0.0715
121								0.0175	0.0286	0.0673	0.0664	0.0664
122									0.0252	0.0740	0.0675	0.0675
123										0.0755	0.0765	0.0765
124											0.0675	0.0675
125												0.0664
126												

V. RESULTS AND DISCUSSION

Using the matrix of similarities it is possible to arrange all airplanes according to their level of risk in respect to others. The lower the risk index, the higher ATC priority should be given to the particular aircraft as it was designated before: 1 means that the airplane has no risk in respect to others and 0 means that the flight has been evaluated as dangerous.

For example, if airplane 118 is taken as a subject, the sequence in which ATC should provide service to others could be as follows: 116 (0.0380), 114 (0.0428), 113 (0.0510), 115 (0.0715), 117 (0.0615), 121 (0.0175), 125 (0.0715), 126 (0.0715), 122 (0.0790), 124 (0.0790), 123 (0.1240).

The analysis of ATC work has shown that it is necessary to classify ATC specialists and ATC centers according to their ability to provide safe enough service using time methods. [17] Therefore, it is necessary for ATCOs to work in a team so that each member of the group could see what their colleagues are doing and would be able to plan his/hers own strategy.

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