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Collision Avoidance Concept for the ATC Expert System

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Introduction

Recent technological, economical and social advances cause serious increase of air travels in the world. From the one hand great development of technical aids such as on-board computers that are called as Flight Management System (FMS) and Global Positioning System (GPS) gives new and more flexible abilities for air traffic operations. Even commercial air traffic carriers consider that a major component of the future air traffic control system will be the "free flight" concept. Consequently, separate aircraft or the whole air traffic flow would have more efficient routes in response to changing conditions. But from the other hand the loss of an airway structure may make the process of detecting and resolving conflicts between aircraft more complex. Consequently, high technology automated conflict or collision detection, avoidance and resolution tools will be required to support aircraft or ground staff in providing safe separation.

Nowadays the Air Traffic Management (ATM) system is built around a rigidly structured airspace. The core gear in the ATM service is human operator. And the rising demand for air travel is stressing ATM and following serving ground staff. Accordingly, increasing workload of the air traffic control officer (ATCO) cause the risk of occurrence of safety problems caused by human factor. It is important to maintain safety levels and increase capacity of congested airways and traffic zones. So there is serious work on future ATM to replace conventional management schemes by progressive computer-integrated ATM systems.

A number of different modelling approaches have been developed and applied in the past for aerospace operations. These models include a wide variety of mathematical techniques for different steps of air travel, but almost all of them were separate products and hardly connectable among themselves.

The aim of the current research is to find new ways of developing automated systems in ATM, which could be base for future ATC. The core purpose is to investigate all air traffic control operation stages and construct proper and accurate mathematical models.

Traffic Environment

The focus of the present modelling methodology is on development of new air traffic control tools that is based on expert system. To develop current model it is important to find the source of data for ATC processing tool. The traffic simulation is used to produce incoming data and is slightly involved in traffic state processing. We do not need collect data from sensors, recognize and decode signals. Simply it is possible to use traffic simulator. The point-mass aircraft model could offer cheaper and more obvious object with appropriate dynamical effects. Such kind of models is very popular and useful for theoretical use in aircraft operation and performance evaluation work.

The current model shown in Fig.1 assumes that the thrust is directed along the velocity vector and that the earth is flat [1–4].

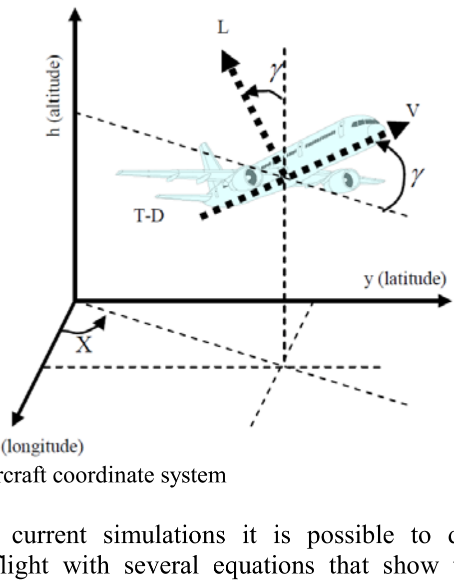

Fig. 1. Aircraft coordinate system

For current simulations it is possible to describe normal flight with several equations that show the full dynamic motion of point-mass objects:

$$\dot{x} = V \cos\gamma \cos\chi , \quad (1)$$

$$\dot{y} = V \cos\gamma \sin\chi , \quad (2)$$

$$\dot{h} = V \sin\gamma , \quad (3)$$

$$\dot{\gamma} = \frac{g}{V}(n\cos\varphi - \cos\gamma), \quad (4)$$

$$\dot{\mathrm{X}} = \frac{g}{V}\frac{n\sin\phi}{\cos\gamma}, \quad (5)$$

$$\dot{V} = \frac{(T-D)}{m} - g\cdot\sin\gamma, \quad (6)$$

$$\dot{n} = \frac{L}{gm}, \quad (7)$$

$$m = -Q. \quad (8)$$

Each aircraft has own ground speed V that is assumed to be the same as airspeed to simplify source data model. Current x, y and h are the components of the position of the centre of gravity of the aircraft in a ground-based reference frame. x is the down range, y is a cross range. All angles are defined with respect to the same frame. From the Fig.4 it is clear that bank angle is φ, the heading angle is X and γ is the flight-path angle. T is the thrust that is produced by aircraft's engine. Opposite force to the thrust is the aerodynamic drag D. g is the acceleration that is caused by gravity. And opposite gravity of the Earth is vehicle's lift L. The important parameter of point-mass object is current object's mass m. It is important to understand that the thrust depends on the altitude h and Mach number M. Q is the fuel flow rate that depends on engine thrust and altitude of flight. The control variables for each separate aircraft are the bank angle, which is produced by rudder and ailerons trims, the thrust that is caused by the engine throttle and the load factor n is controlled by elevators. It is the basic point-mass object that could be adapted and simplified for any simulation needs.

To simplify case study of collision or conflict avoidance concepts, model is based on 2-D plane motion Fig.2. The most popular system called TCAS is core of the used mathematics. The main idea of the safety issues is to maintain correct vertical or horizontal separation between each aircraft. Vertical separation is 1000 ft (300 m) below altitude 29000ft and is twice greater (2000 ft) above mentioned altitude. According to the ICAO (International Civil Aviation Organization) data altimeter errors, e, of one aircraft belongs to Laplacian probability distribution

$$p(e) = \frac{1}{2\lambda}\exp\left(\frac{-|e|}{\lambda}\right), \quad (9)$$

where λ is a statistical parameter based on altitude.

In our case we will operate with horizontal motion. So we need to point the main parameters of dynamic system. Firstly horizontal separation of standard situation between aircraft should not exceed dS=5 Nm (1852 meters). There is 2.5 Nm buffer zone around each aircraft. To operate with separate parameters of aircraft location and dynamic we use indexes of aircraft i=1..Na and j=1..Na (Na is amount of aircraft and i≠j).

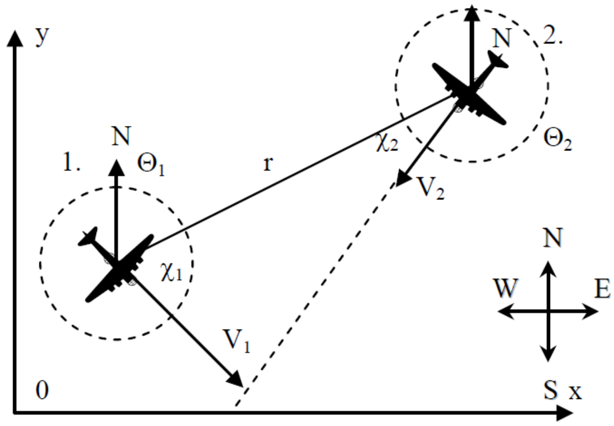

Fig. 2. Horizontal plane

All aircraft has coordinates x and y and have velocity vectors $\nu_i=[\nu_{xi}, \nu_{yi}]$. The relative location of the aircraft is expressed in range r between aircraft and bearing χ that is angle from direction of motion or direction of speed ν of first aircraft and position of second aircraft

$$r_{ij} = \sqrt{x_{ij}{}^2 + y_{ij}{}^2}. \quad (10)$$

Relative velocity between aircraft is

$$V_{r(ij)} = \sqrt{(v_{x(j)} - v_{x(i)})^2 + (v_{y(j)} - v_{y(i)})^2}. \quad (11)$$

It is possible to calculate time to conflict in current situation of motion

$$t_{to\_conflict(ij)} = \frac{r_{ij}}{V_{r(ij)}}. \quad (12)$$

Θ is magnetic or true bearing from the north to the converging or just checked traffic in the area. Those all are required to discover attitude between aircraft and decide if aircraft is from the right or left side of direction of motion.

It should be clear that current mathematics is a base of required data for conflict detection. In real flight the major horizontal position uncertainty depends on the wind, for which a complete and fully precise model is not available yet. But it is possible to use the sum of large number of independent random perturbations and in models it is expected to be Gaussian.

To determine horizontal position uncertainty it is possible to describe 2D Gaussian distribution of location of aircraft

$$f(x,y) = Ae^{-\left(a(x-x_0)^2 + 2b(x-x_0)(y-y_0) + c(y-y_0)^2\right)}, \quad (13)$$

where coefficient A is a height of the peak and (x_0,y_0) is a centre of the blob or another words, it is the position of current aircraft. Coefficients a, b and c could be found from:

$$a = \frac{\cos^2\varphi}{2\sigma_x^2} + \frac{\sin^2\varphi}{2\sigma_y^2}, \quad (14)$$

$$b = -\frac{\sin 2\varphi}{4\sigma_x^2} + \frac{\sin 2\varphi}{4\sigma_y^2}, \quad (15)$$

$$c = \frac{\sin^2 \varphi}{2\sigma_x^2} + \frac{\cos^2 \varphi}{2\sigma_y^2}. \quad (16)$$

Or in general numeral calculations it is possible to use Monte Carlo simulations of uncertainty element wind component of motion.

So the total position of each aircraft could be defined by $P_{ij}(t) \in R^2$. If it is dynamic model and data change in time, we point that heading of system element is changing in time, then X(t) and we get

$$P(t+dt) = P(t) + \begin{bmatrix} \cos(X(t)) \\ \sin(X(t)) \end{bmatrix} \cdot v_{total} \cdot dt + \\ + W(t, P(t)) \cdot dt + N(t, P), \quad (17)$$

where $W(t, P) \in R^2$ is known wind model that is called wind field in the area and N(t, P) is uncertain stochastic wind mixture data that is Gaussian random field.

Conflict basics

Formulated dynamic models are used to get raw or primary data for any expert advisory systems. Actually it is not the main parameters that should be analysed. More important are conflict probability values that are used as criteria for conflict evaluation and resolution. It should be clear that conflict detection is processed between each pair of aircraft that is found and tracked by surveillance system.

The most popular types of conflicts are:

- General probability of conflict — probability of conflict that will occur during the look-ahead time horizon;
- Maximum probability of conflict —maximum value over look-ahead horizon of the momentary probability of conflict;
- Collision probability — probability of collision that occurs during the look-ahead time horizon;
- Incorssing probability — it is defined as the event of one aircraft entering the buffer zone of another. The incrossing probability depends on the incrossing risk, which is the integral over the prediction horizon of the incrossing rate. Incrossing probability is used to evaluate collisions rather than conflicts.

Continuation of mathematical model it is easy to find intersections between motion of aircraft. As was described before all primary data let us find the crossing points on root intersections. It is the simplest model to detect collision.

Another way is to use more complicated proposed in different works models. One of the most popular, which is widely used in simulations, is the Reich Collision Model and later Generalized Reich Model.

It is assumed in the Reich model that aircraft is shaped like a rectangle with dimensions D_1, D_2 and D_3 that describe length, width and height of the box. It is assumed that aircraft are touching when one aircraft is in the front the other by a distance that is less than length of the box. Similar notation could be addressed to touch by side or touching by bottom or ceiling of the box.

The incrossing probability depends on the joint probability density function

$$f(r_{ij}, V_{r(ij)}) \equiv f(r_{x(ij)}, r_{y(ij)}, r_{z(ij)}, v_{x(ij)}, v_{y(ij)}, v_{z(ij)}). \quad (18)$$

Mentioned Reich model describes that the density is independent in the x,y, and z dimensions

$$f(r_x r_y r_z v_x v_y v_z) \equiv f_x(r_x, v_x) f_y(r_y, v_y) f_z(r_z, v_z). \quad (19)$$

The margin densities (f_x, f_y and f_z) are constant over the dimensions of the aircraft and the density is independent in the position and velocity components. That all creates

$$f(r_x r_y r_z v_x v_y v_z) = f_{rx}(0) f_{ry}(0) f_{rz}(0) f_{vx}(v_x) \times \\ \times f_{vy}(v_y) f_{vz}(v_z). \quad (20)$$

Elements of this model travel along parallel tracks without making turns and orientation of the imagined shape of the collision box stays the same. It is assumed that all shapes are the same size.

Under those facts the total incrossing rate could be calculated as

$$\varphi(t) = f_r(0,0,0) \sum_{k=1}^{3} A_k E|v_k|, \quad (21)$$

where k is three dimensions x, y and z, f_r is the marginal density, and A_k is the area of the face perpendicular to dimensions k. The expected amount of incrossings over the time period t1 and t2 is

$$E_{ij} \int_{t2}^{t1} \varphi_{ij}(t) dt. \quad (22)$$

All aircraft pairs (ij) should be evaluated and sum of them is total expected number of incrossings.

To continue the explanation it is important to point Generalized Reich Model that is not so restrictive as previous one. This model assumes that velocity in one direction depends on velocity in another direction. So the incrossing rate through a single face and its opposite face could be described with

$$\varphi_x(t) = \int_{-D_2}^{D_2} \int_{-D_3}^{D_3} \int_{-\infty}^{0} -v_x f(v_x, r_x = D_1, r_y, r_z) dv_x dr_z dr_y. \quad (23)$$

And total incrossing rate through all faces could be taken as

$$\varphi(t) = \varphi_x(t) + \varphi_y(t) + \varphi_z(t). \quad (24)$$

The role of expert system

So in previous section of the work it was discussed about secondary data processing of aircraft flight information. Firstly we found stochastic parameters of an aircraft. Secondly it was necessary to adopt them for expert system tool. Finally, we get criteria — conflict probability that could be easily analysed and evaluated by fuzzy systems. For example, there are two aircraft with known relative distance, speed and angles of motion between each other. It is possible to find conflict probabilities in current traffic situation. Accordingly by mathematical calculations it is possible to find advised heading or altitude change that could be checked and evaluated for conflict probability. Expert tool chooses the most appropriate action, which will take the least time and probability of conflict. The principal work of expert system is to find optimal way of conflict solution, which will be similar to human operation decision.

Conclusions

This paper is continuation of previous work on developing expert systems as safety tool in air traffic control. The main idea is to adopt real life stochastic parameters in understandable way for high level of safety automated systems. This paper describes mathematical model of required data for processing through several stages of adoption. Simplified the destination of this development, air traffic control functions could be executed by non-human operator. Moreover, proposed design could be used as basic stages of producing appropriate real ATC expert system.

Future work on this topic will be conducted with discovering optimal conflict detection and resolution algorithms and implementing them in the serious models of expert ATC systems. It is important to find out effective algorithms and strategies for conflict detection and solution process. Furthermore, it is quite important to choose the correct expert system software. That is serious investigation plan for development of real expert system for future air traffic control, where safety and automation level be increased by using intelligent computer technologies.

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Despite the fact that there is unimaginable technological achievement in communication, navigation, surveillance, computation and control, the ATM system suffers from the lack of automation abilities. Almost all main processes of ATM are based on a rigidly structured airspace and centralized human-operated system architecture, but increasing the level of automation we could improve the efficiency of ATM and the human-operator tasks could be simplified. The core objective of any ATM is to guarantee safety and efficiency. The main purpose of this work is to provide theoretical investigation of serious questions in ATC system and in ATC working process. This publication is a continuation of previous work on concept of expert systems that could be used in ATC. Using appropriate knowledge in ATC physics, procedures and technology processes the ways to increase efficiency of Air Traffic Control (ATC) are found that do not destroy the safety level of whole ATM. The analysis of conflict characteristics, collisions and avoiding actions will be a knowledge base for future ATC expert system. Logical expert systems are similar to human operators that are using own knowledge bases, not mathematical functions, and are flexible for solving different typical problems of normal life. Ill. 2, bibl. 4 (in English; abstracts in English and Lithuanian).

I. Sinuks. Lėktuvų susidūrimo išvengimo koncepcijos taikymas ore esančių priemonių srautų valdymo sistemose // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 2(108). – P. 7–10.

Ryšių, navigacinės, skaičiavimo ir kontrolės sistemos sparčiai tobulėja, tačiau tarpusavyje jos automatizuojamos ribotai. Beveik visų sistemų procesai ir veikimas yra griežtai reglamentuotas ir valdomas žmogaus operatoriaus. Tokios sistemos efektyvumą galima padidinti didinant autonomiškumo ir automatizavimo laipsnį. Analizuojami automatizuotų sistemų ir jose vykstančių procesų teoriniai aspektai. Analizuojamas ore esančių priemonių srautas ir siekiama padidinti efektyvumą taikant bendrąsias fizikos žinias, procedūras ir technologinius procesus. Sutelkta informacija apie konfliktines situacijas, susidūrimus ir kaip jų išvengti turės išliekamąją vertę būsimiems tyrimams. Loginės ekspertinės sistemos yra ekvivalenčios žmogaus operatorius sistemoms, kurios taiko ne matematines išraiškas, o konkrečias duomenų bazes. Il. 2, bibl. 4 (anglų kalba; santraukos anglų ir lietuvių k.).