Synergy of Piloted, Remotely Piloted and Unmanned Air Systems in Single Air Navigation Space

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A synergistic approach to the organization of autonomous free flight operation of manned, remotely piloted and unmanned vehicles in modern air navigation space is presented in this article. The conditions for the implementation autonomy properties of the flight crew activity to resolve the conflicts with other aircraft are considered.
Keywords: conflict resolution, free flight, synergetic approach, autonomous aircraft.

1. INTRODUCTION

The solidarity of all members of the modern world air transportation system is a fundamental property to achieve maximum economic benefits and safety. However, there are objective factors which have an essential impact on the processes of air traffic organization:

- an increase of flying intensity is taking place now. This fact leads to an inevitable increase in the number of the aircraft conflicts collision, and the term "conflict" is transformed into the concept of "polyconflict";
- the world aviation community makes demands [1, 2] concerning the transition from the flight regulated aircraft trajectories to their free flight and the board autonomy increase (the concepts of «Free Flight», «Free Route», «A^3»). This is expressed in delegate the rights for the crew to choose the flight path, the speed and flight profile based on economic and other interests, as well as invest with the problems of advanced conflict resolution on the current and future board automated systems (such ASAS - Airborne Separation Assistance System, or Airborne Surveillance Applications System and ADS-B - Automatic Dependent Surveillance - Broadcast). According to the forecasts of Eurocontrol specialist's gradual redistribution of the conflicts detection and resolution between the ATC and the crew will be held. Common plan of FAA and Eurocontrol actions up to 2030 [3] foresees full transfer of the tasks the conflicts resolution between the aircraft from the land to the board;
- new organizational and computer technologies of global air traffic control is being developed. They are aimed at providing flexible, coordinated (not regulated) air space exploitation taking into account the interests of all users of CNS/ATM;
- the development and use of new aviation robotic systems that operate without a pilot on board is being enhanced, e.g., UAV (Unmanned Air Vehicle), UAS (Unmanned Autonomous Systems), RPAS (Remotely Piloted Air Systems) [4 - 7].

All the above mentioned processes necessitate the finding of new ways of the air traffic organization at the global system level.

This paper deals with the use of self-organization principles (synergy) to form a new image of air navigation space, conferring the aircraft to operate free and autonomous flights.

2. THE REVIEW OF SYNERGETIC APPROACHES

The idea of self-organization approach for the conflict resolution during the air traffic control in the Single Air Navigation Space (SANS) was firstly proposed by M. Eby [8]. In his understanding the aircraft self-organization in the aeronautical environment is realized through individual actions of each aircraft to achieve their goals for a given level of safety, but not through a plan imposed on the aircraft from outside. He offers to use potential properties of electric fields as a self-organization model of the SANS. The essence of these properties is the presence of the attractive forces between heterogeneous charged particles and the repulsive forces between the charged particles in the electric field. The aircraft presents as like-charged particles and their targets (aerodromes, intermediate routes (enroute waypoint etc.) are assigned by opposite charges.

A synergetic approach proposed by A. Kolesnikov for laws control synthesis of the nonlinear dynamic objects is also known [9]. This approach is based on the procedures of the "expansion" and "contraction" of a phase space. The laws of the energy conservation are the foundation of the proposed solutions. The physical content of the "extension" procedure means that sufficient resources (in general - energy resources) are needed for the implementation of desired (target) motion in the system. Energy resources system must ensure the compliance with the provisions of its functions and the achievement of its desired goals. The introduction of energy as an additional phase coordinate into the control model is the essence of the "expansion" phase space. The introduction of additional phase coordinates gives the system new dynamic properties. Enhanced system reduces the number of available freedom degrees, i.e. it receives asymptotically stable motion to the desired diversity in large phase states under the action of the synthesized synergistic. The "compression" of a nonlinear system phase space is the system control process with a regard to its internal nonlinear dynamic properties.

In thermodynamics, G. Haken [10] and I. Prigozhyn [11] as the founders of the synergistic approach postulate the selection of complex system parameters of the "order" from a common set of the parameters. The energy and entropy as the main system-wide parameters of the «order» are offered. They act as a backbone basis of the self-organization system.

The analysis of existing synergistic approaches shows that the achievement of self-organization effect in SANS should be based on the characteristics of the energy interaction of its elements.

3. SELF-ORGANIZATION IN PHYSICAL SYSTEMS

The matter itself is a typical example of the self-organization principle in nature. Let's examine more closely the model of "Brownian motion" of the gas molecules as a prototype of the "Free Flight" concept implementation. In this example, the motion of the gas molecules is analogous to free movement of the aircraft autonomous motion in SANS. Gas molecules in a state of thermal chaotic motion constantly collide each other. However, in molecular physics, the term "collision" relatively to the molecules is not a process similar to the collision of hard spheres. The molecules collision is the process of interaction between the molecules at a distance in which the molecules change their direction of motion and the velocity module. [12]

The molecules similarly interact in the substances that are found in other states of aggregation (solid, liquid). The molecules interaction is determined by intermolecular attractive and repulsive forces. It is important that these forces operate simultaneously. General character of the attractive force from the distance for different molecules is qualitatively the same: the attractive force of molecules to each other dominates at large distances between them and the repulsive force act at short distances. In Fig. 1 the qualitative dependence of intermolecular interaction forces from the distance r between two molecules is presented, where W and F – are the dependence of the repulsion and attractive forces respectively, and $W+F$ - is a resultant force.

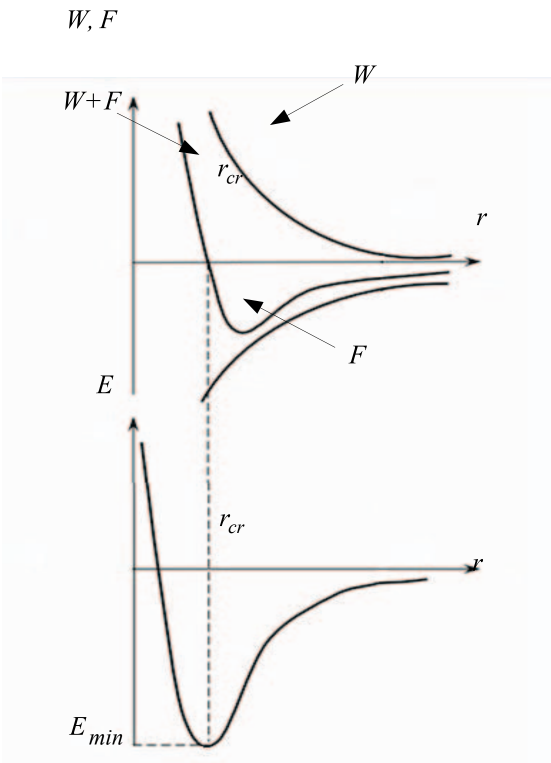

Fig.1. The dependence of the attractive forces, the forces of repulsion and the energy interaction of the molecules from the distance between them. Source: [13]

At a critical distance $r = r_{cr}$ the resultant force is equal to zero, i.e. the attractive and repulsive forces are counterbalanced. This distance r_{cr} corresponds to the equilibrium distance between the molecules, where they would be in the absence of thermal motion. The parameter r_{cr} is specific to the structural elements of a microcosm because at this distance the interaction of their energy is a minimum. Potential energy curve *E*(*r*) has specific form (Fig. 1) and is called the "potential hole" [14]. Thus, structural stability of synergistic properties of the microcosm elements on account of minimizing the interaction energy of the molecules at a distance r_{cr} has a significant importance [15]:

where *a*, *b* – are the model coefficients; m, n – are natural numbers.

To ensure equilibrium condition of the microcosm elements, the basic condition *m*> *n* must be done. This condition defines a synergistic aggregate state of physical microsystems.

4. ENSURE SYNERGISTIC PROPERTIES OF THE OBJECTS IN THE AIR NAVIGATION ENVIRONMENT

The above mentioned property of a microcosm self-organization should be used to ensure synergistic properties of the objects in the air navigation environment.

Let's choose limited area of air navigation space where there are goal-seeking moving dynamic objects (piloted and unmanned aircraft), their target positions, as well as tough, flexible, static and dynamic constraints which are present in a given space. This set of objects will be considered as a system where the elements are designed to solve common system problems of the aircraft autonomous flight provided that safety and benefits.

Aircraft movement in general can be presented by kinematic equation system

$$\frac{dx_{1i}}{dt} = f\left(x_{1i}(t), u_{1i}(t), \xi_{1i}(t)\right);$$
$$\frac{dx_{2i}}{dt} = f\left(x_{2i}(t), u_{2i}(t), \xi_{2i}(t)\right); \quad (1)$$
$$\{u_{1i}, u_{2i}\} :\Leftrightarrow \{\Psi_i, V_i\};\ 0 \le \Psi_i \le 2\pi;\ 0 \le V_i \le V_{i\,max};$$
$$\frac{d\Psi_i}{dt} \le max\left(\frac{d\Psi_i}{dt}\right),$$

where x_{1i}, x_{2i} - are the coordinates of the *i*-th aircraft; u_{1i}, u_{2i} - is a required conflict-free aircraft traffic control, which would ensure the safety and the aircraft achievement of the target destination; V_i - is a flight-path velocity vector of the *i*-th aircraft; $V_{i\,max}$ - is maximum permitted value of a speed of the *i*-th aircraft; Ψ_i - the angular position of the vector V_i; $max\left(\frac{d\Psi_i}{dt}\right)$ - maximum permitted value of the angular velocity vector V_i; ξ_{1i}, ξ_{2i} - are the disturbances which effect on the *i*-th aircraft (in the coordinates x_{1i} and x_{2i} respectively).

The value (module) of the velocity vector and the angle of its orientation (course angle) are the control parameters in the kinematic model of the AC motion (1). In the process of implementation of the free-flight condition, the angular position of the velocity vector in the model (1) is defined as the sum of:

$$\Psi_i = \Psi_{i\,g} + \Delta\Psi_{i\,nc}, \quad (2)$$

where $\Psi_{i\,g}$ - is the course angle characterizing the direction of the velocity vector to the target point of the flight (aerodrome, waypoint, etc.); $\Delta\Psi_{i\ nc}$ - is the course angle increment, providing AC conflict-free movement between each other and the avoidance of obstacles and restrictions in the air navigation space (self-separate operations from traffic, weather and airspace).

The speed in free flight (especially during the "cruise") is selected by the aircraft operators on the basis of flight economic parameters, such as the cost index CI (Cost Index). Intense changes of the flight speed at a polyconflict resolution lead to the increase in fuel costs and the decrease of the flight efficiency (profitability). Therefore, the independence (autonomy) of the control loop circuits by the velocity vector and its angular position is one of the main requirements that are made on the polyconflict resolution methods.

Let's formalize the system in the form of virtual gravity model. Each SANS object (aircrafts, target positions, obstacles, restricted areas) is presented in the model as *i*-th material particle (or their combination), endowed with its own mass m_i and gravitational potentials of attraction U_i^+ and repulsion U_i^-:

$$U_i^+ = \frac{Gm_i}{r_{ij}},\ U_i^- = -\frac{Gm_i}{r_{ij}}. \tag{3}$$

where G - is a constant; r_{ij} - is the distance between material particle.

Let's neglect the mutual influence of the fixed particle. We will not consider the effect of the *i*-th material particle on the motion of gravitational forces particle of the target positions of the other material particle.

In this case, each *i*-th variable material particle will be affected by the repulsion and attractive forces:

$$F_{ij} = \frac{Gm_i m_j}{r_{ij}^m} = U_i^+ \frac{m_j}{r_{ij}^{(m-1)}};$$

$$W_{ij} = \frac{Gm_i m_j r_{cr}}{r_{ij}^n} = U_i^- \frac{m_j r_{cr}}{r_{ij}^{(n-1)}}. \tag{4}$$

Total graphic image of the gravitational field, formed by one material particle, is shown in Fig. 2.

Every particle of the gravity model is characterized by the total potential of the artificial gravitational field, and the movement direction of material particle in this field corresponding to aircraft mass centre in the SANS caused by the effect of the repulsion and attractive forces on them from other material particle.

To provide goal-oriented movement of each *i*-th particle it is necessary that the attractive force of its target position at the distance $r_{ij} \geq r_{\mathrm{cr}}$ will be greater than maximum total attractive force N of the other particle

$$F_{ig}^+ > max \sum_{j=1}^{N} F_{ij}^+ ,\ i \neq j. \tag{5}$$

In view of (4) we rewrite (5) in expanded form

$$\frac{Gm_i m_{i\,g}}{r_{i\,g}^n} > max \sum_{j=1}^{N} \frac{Gm_i m_j}{r_{ij}^n},\ i \neq j, \tag{6}$$

where $m_{i\,g}$ - is the mass of the target position of *i*-th dynamic particle; $r_{i\,g}$ - is the distance between the *i*-th dynamic particle and its target position. Under the condition $m_i = m_j = 1$ we'll get the required values of the target positions masses of dynamic particle

$$m_{i\,g} > max \sum_{j=1}^{N} \frac{r_{i\,g}^n}{r_{ij}^n},\ i \neq j. \tag{7}$$

Providing $m_i \neq m_i$ the inequality (7) will be as follows

$$m_{i\,g} > max \sum_{j=1}^{N} \frac{m_i m_j r_{i\,g}^n}{r_{ij}^n},\ i \neq j. \tag{8}$$

The conditions (6) and (7) eliminate drawbacks of the force fields, such as the presence of local minima, the "course", the "plateau", and provide guaranteed achievement of goal positions.

The gradient lines of synthesized force field characterize the energy distribution of the material particle interaction. The direction of the field gradient at any specific time determines conflict-free flight paths of every movable particle in this field.

At the approach of the material particle to the critical distance r_{cr} the resultant force effecting on them is equal to zero, i.e. the repulsion and attractive forces counterbalance each other. It is the principal feature and the advantage of such force field.

Critical distance r_{cr} determines the size of the protection zone (safety zone) of each aircraft in the SANS. The sizes of the protection zones must meet the requirements of modern separation standards determined in this navigation area. [16]

The absence of border crossings of the protection zones allow to maintain guaranteed level of air traffic safety in the free flight areas.

$\frac{d}{dt}\frac{\partial L}{\partial \dot{\Psi}} - \frac{\partial L}{\partial \Psi} = 0$ gives the dynamics of the conflict-free angle of aircraft velocity vector

$$\frac{d^2\Psi}{dt^2} = -grad(U). \tag{10}$$

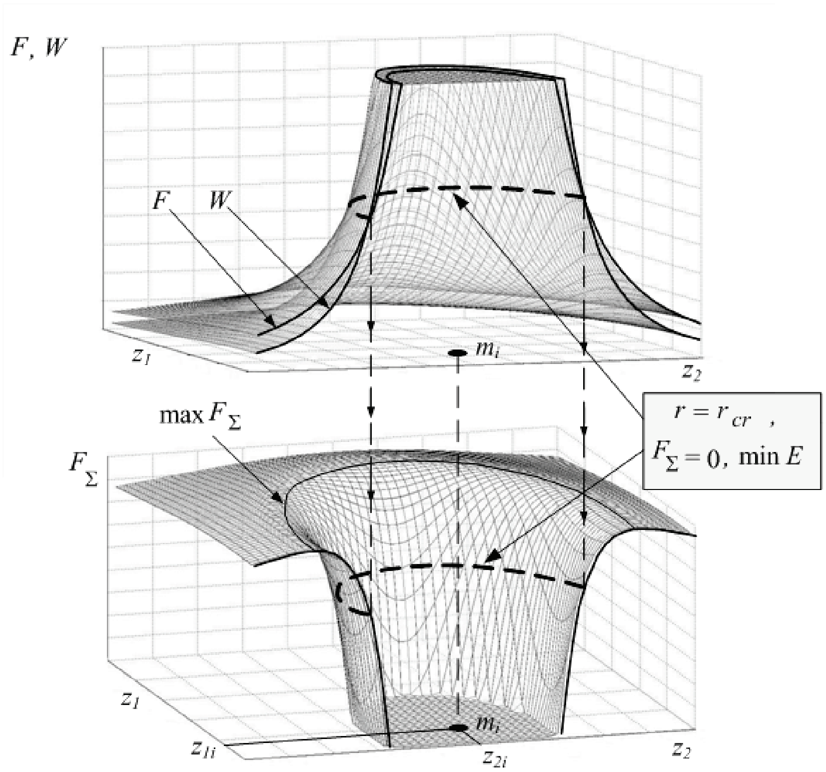

Fig. 2. Surface levels of artificial gravity field generated by i-th material particle
Source: Own work

Based on the positions of classical physics, the gravitational potential - is a scalar function, which is the ratio of the body potential energy to the mass of the body.

The movement of the body with the mass in the gravitational field is defined by the Lagrange function, which in the inertial reference system is given by

$$L = \frac{m\dot{\Psi}^2}{2} + m\ U\ , \tag{9}$$

where m - is a body mass; Ψ - is the gradient direction angle of the gravitational field; U - is the gravitational field potential.

The substitution (9) in the Lagrange equation

5. CONDITIONS AUTONOMY BOARD

The achievement of the SANS synergistic properties, given by the equations (1) (2) and (10) is not possible without the coordination movement of all objects. The autonomous polyconflict resolution on board depends on the development degree of on-board avionics.

The board autonomy requires the resolution of the polyconflicts of aircrafts collision avoidance without the controller. Such functions and responsibilities reallocation provides that the construction of the conflict-free flight paths and the coordination of their manoeuvres should be carried out by the on-board systems and the pilots.

The implementation of the board autonomy requirements provides appropriate computer equipment (hard) and algorithmic supports (soft) for the autonomous problem resolution of the flight including the problems of free flight path and polyconflict autonomous problems.

Synergetic approach of the air traffic management in aeronautical environment is proposed in the paper. It can be implemented both on board and the ground automated control points.

6. THE SUMMARY

In this paper the authors discussed the synergy of piloted and unmanned air systems in single air navigation space.

Method of the aircraft conflict resolution plays a key role in getting their synergistic properties.

Proposed approach to create artificial gravity fields regardless of the number of aircraft in the conflict in a limited airspace, allows to provide:

- the problem solution of "damnation of dimensionality" and the elimination of the "domino effect" in the polyconflict resolution;
- aircraft control loops autonomy and the energy costs minimization of the conflict-free flight paths;
- focus on aircraft priority;
- safe safety movement of various classes of dynamic objects such as piloted and unmanned aircraft, space, ground, surface and underwater vehicles, mobile robots.

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