Method of the Multi-UAV Formation Flight Control

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Abstract. The main issue that arises when considering multi-UAV formation flight in a group is that of collision probability. In this case, without human control involved, it is artificial intelligence that is responsible for flight performance in the airspace in such a way that collision is avoided. Taking into account a rapid increase in civil and military applications of UAVs, a collision avoidance algorithm is proposed based on artificial potential field method. This method makes it possible to detect a potential conflict between multiple vehicles and other static or moving obstacles found in airspace, to provide collision resolution by changing UAVs flight parameters through maintaining minimum separation distance, including cases when manned vehicles are found in the same airspace. There can be distinguished a wide range of obstacles: static non-moving objects or vehicles having different sizes or flight parameters (multi-rotor, fixed wing and single rotor UAVs), or a few UAVs of one type but with different types of hardware configuration, at the same time considering the possibility of flight performance in the same airspace with manned aircraft. Group formation keeps shape on the flight path, taking into account some ground speed restrictions and turn bank angle values according to UAV's flight performance characteristics. The proposed method is used for multi-UAV control without any leader and provide multiple conflicts resolution, where each UAV is characterized by its protection zone.

Keywords: autonomous unmanned aerial vehicle, artificial potential field, synergetic, formation flight control.

1 Introduction

Remotely Piloted Aircraft System (RPAS) or Unmanned Aircraft System (UAS), colloquially known as 'drones', are aerial vehicles that fly without an on-board pilot, as well as the systems that support them to do so. RPAS refers to a system, extending beyond the Remotely Piloted Aircraft (RPA) or Unmanned Aerial Vehicle (UAV) to include ground stations (where control units and remote pilots are based) and communications infrastructures. Within the broad definition of UAS lies a diverse range of systems and UAVs. Some differences between these UAS are immediately apparent, such as the size or weight of UAVs. Other differences are more subtle, such as the medium of communication between the vehicle and the ground station. These systems have varying degrees of automation and autonomy, but usually include human remote pilots who control the vehicle from meters, kilometers or continents away. Perhaps the most established and visible applications of UAS are for military purposes, including combat and surveillance operations, but many applications have been identified for domestic uses such as environmental monitoring, security, emergency response, surveillance and recreation. In addition to the significant functional and economic benefits of these civil UAS, the technologies required for civil UAS operations are ready for market and the principal barriers to development in the sector are regulatory. In response to demand, the European Commission (EC) has published strategies to allow the gradual integration of UAS into normal airspace.

The main technical peculiarity of UAS is defined by the extent of autonomy and automation delegated from the pilot to the system. Automation levels range from those that are fully piloted from a remote location to those that are fully automated. There are also several points in-between, with some maneuvers triggered automatically through autonomous monitoring of conditions. Depending upon system priorities, autonomous maneuvers may have priority over, or be overridden by, the commands of a remote pilot. The International Civil Aviation Organization (ICAO) and current EC plans will only permit autonomous maneuvers to override pilot command in extraordinary circumstances such as communication failure or imminent collision risk. The UAS technologies beyond this definition, featuring greater autonomy, are also quite well developed and, while integration is not currently planned, it could plausibly follow a successful period of development in the UAS sector [1].

2 Analysis of Researches and Publications

The results of analysis show that most of known methods for multi-UAV control have a number of significant limitations that are connected with multiple conflicts resolution and group formation. Particularly, the main disadvantage that potential conflicts can be solved pairwise, when this issue needs to be done in a global way. For example, the system called Traffic Alert and Collision Avoidance System (TCAS) that is already installed aboard uses range measurements and range-rate estimates to determine if a conflict exists [2]. Methods developed for group control in robotics do not include such feature, so UAVs must deal with constant movement and limited turning ability, which makes collision avoidance much more complicated [3].

The classical approach is called geometric, in which aircraft trajectory predictions are based on linear projections of the current vehicle states [4-5]. The major disadvantage is that prediction errors are negligible only for short time periods and require high rate of surveillance information update. The class of stochastic approaches is related to the problem of probabilistic conflict detection in the presence of various uncertainties during the flight. The aircraft dynamics are described by using stochastic differential equations, and the future aircraft's trajectory is determined by solving the stochastic trajectory optimization problem, it could be applied for conflict definition at rather big distances [6], so stochastic approach can hardly be applied in order to control a group of UAVs flying close to each other.

Linear programming is a mathematical method [7] where optimal control problem lies in finding trajectories that minimize objective function. The drawback of such approach is the flyability of the optimal trajectories as far as safety and performance aspects of a given flight route are concerned.

The common disadvantage of all these methods is that they do not meet the main requirements with respect to autonomous UAVs: the absence of any communication links with the appropriate ground stations, with on-board computational and power sources being limited.

The summarized disadvantages of the analyzed methods make it impossible to simultaneously use a combination of such parameters as heading, speed and altitude change maneuvers to resolve multiple potential conflicts. Therefore, it is necessary to develop some new methods for multiple autonomous UAVs control in a group in a three-dimensional space. The method developed in this article is the evolution of potential field method proposed in article [8]. A potential fields approach is based on assigning magnetic or electrical charges of the same sign to UAVs, while the opposite charges are assigned to destinations, with the principle being based on the laws of physics according to which the like particles will repel each other, while the destinations having opposite charges will attract them. The main feature of such approach is that UAVs do not necessarily need to know the positions of all other aircraft, so artificial force generated by each UAV allows them to avoid each other spontaneously, at the same time keeping a group form [9]. According to [10], this approach is scalable and can be applied to a big number of UAVs, even in case of multiple conflicts.

3 Problem Statement

To solve this problem, a potential field approach is used. This method uses the property of the real world charged particles to generate a force field (electric or magnetic), which causes attraction and repulsion forces when these particles interact. The matter itself is a typical example of the self-organization principle in nature. UAVs are considered as dynamic objects with the same sign, with the point of destination having the opposite sign, it is analogous to the free movement of the aircraft autonomous motion where they constantly have potential conflicts, and it is required to avoid collisions with other dynamic objects or static/dynamic obstacles. In this case, the term 'potential conflict' is a situation, when the minimum separation standard between dynamic objects is violated. The protection zone of dynamic objects is generally defined as follows: the minimum allowed horizontal separation and the vertical separation requirement depending on the sizes of dynamic objects. The dynamic objects collision is the process of interaction between the dynamic objects or obstacles at a distance in which the dynamic objects change their direction of motion and the speed module.

The dynamic objects interact similarly to the particles of substances that are found in other aggregate states of matter (solid, liquid). The forces act simultaneously. For different dynamic objects, the general character of the force of gravity from distance is qualitatively the same: the force of attraction between dynamic objects dominates at large distances, while the force of repulsion acts at short distances. Fig.1 shows the qualitative dependence of interaction of forces between two dynamic objects found at distance r between two dynamic objects is presented, where F^+ and F^- – are the dependence of the attraction and repulsion forces respectively, and $F^+ + F^-$ - is a resultant force. At a critical distance $r = r_{cr}$ the resultant force is equal to zero, i.e. the forces of attraction and repulsion are counterbalanced. This distance r_{cr} corresponds to the equilibrium distance between the dynamic objects.

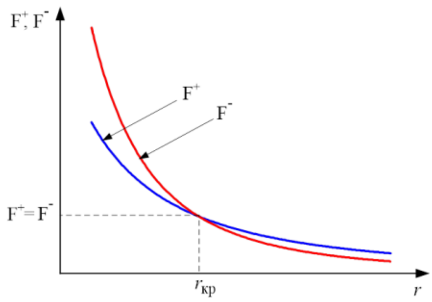

Fig. 1. The dependence of the attraction forces, the forces of repulsion between dynamic objects acting at a distance

This article considers a group system consisting of n autonomous UAVs, with a point-mass model used to describe UAV formation movement. The related variables are defined with respect to the inertial coordinate system and are shown in Fig. 2.

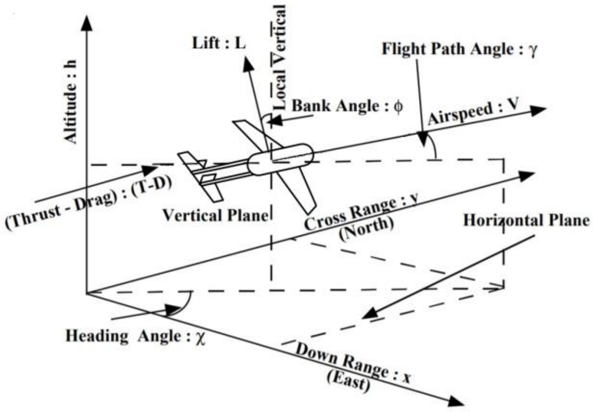

Fig. 2. UAV coordinate system

The point-mass UAV model captures most of the dynamical effects encountered in civil aviation aircraft. The point-mass equations of motion are formulated with respect to a coordinate system shown in Fig. 2. The point-mass model assumes that the UAV thrust is directed along the velocity vector, and that the UAV always performs coordinated maneuvers. It further assumes a flat, non-rotating earth. These assumptions are reasonable for UAVs operating within different ranges, therefore, this method can be used in conflict resolution between different types of UAVs, with the fidelity provided by the point-mass model being adequate for formulating these problems.

Point-mass models applicable for spherical earth approximations can also be developed. The fuel expenditure is negligible, i.e. the center of mass is time-invariant [11]. Under these assumptions, the motion equations of the *i*-th UAV can be described as follows:

$$\begin{aligned} \dot{x}_i &= V_i \cos\gamma_i \cos\chi_i\,; \\ \dot{y}_i &= V_i \cos\gamma_i \sin\chi_i\,; \\ \dot{h} &= V_i \sin\gamma_i\,; \\ \dot{\gamma} &= \frac{L_i \cos\varphi_i - g m_i \cos\gamma_i}{V_i m_i}; \\ \dot{\chi} &= \frac{L_i \sin\varphi_i}{m_i V_i \cos\gamma_i}; \\ \dot{V} &= \frac{T_i - D_i}{m_i} - g \sin\gamma_i\,; \end{aligned} \tag{1}$$

where: i=1, 2, …, n is the index of multiple UAVs under consideration. x_i, y_i, h_i denote the components of UAV gravity center position. For i-th UAV, x_i is down range; y_i is cross range; h_i is altitude; V_i is ground speed; γ_i is flight path angle; χ_i is heading angle; T_i is engine thrust; D_i is drag; m_i is mass; g is acceleration due to gravity; φ_i is bank angle; L_i is vehicle lift. Bank angle φ_i and engine thrust T_i are control variables for an aircraft. Bank angle is commanded via combining rudder and aileron trims, thrust is commanded by engine throttle. The g-load $n_i=L_i/gm$ is controlled by elevator, though it refers only to UAV construction characteristics having higher limits due to the absence of crew on board an aircraft in comparison to traditional application. Throughout the multi-UAV control process, these control variables will be constrained to remain within their respective limits. The most common constraints considered are upper and lower bounds on ground speed (V_i), altitude (h_i), g-load (n_i), thrust (T_i), bank angle (φ_i) and climb or descent rates.

Heading angle χ_i and flight path angle γ_i are computed as:

$$\tan\chi_i = \frac{\dot{y}_i}{\dot{x}_i} \tag{2}$$

$$\tan\gamma_i = \frac{\dot{h}_i}{V_i} \tag{3}$$

In air traffic, conflict resolution is determined by separation constraints, forming the so-called conflict envelopes or ‘protection zones’ so that UAVs flight trajectories do not overlap during the flight. The conflict between two UAVs or an UAV with the above-mentioned obstacles implies that their altitude should differ in value h_{pr} given in UAV flight performance characteristics, or they should not get closer in the horizontal plane than indicated by value r_{pr}. The protection zone can be visualized for each UAV as shown in Fig. 3.

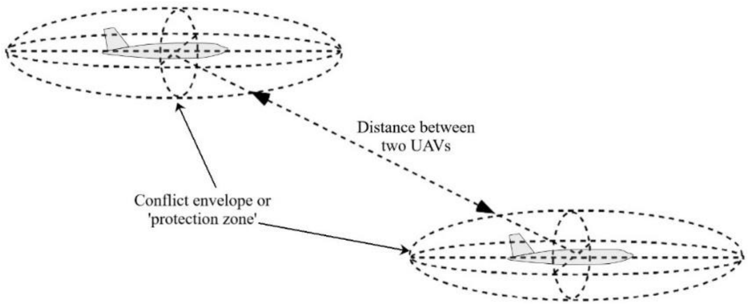

Fig. 3. Spheroidal conflict envelope or 'protection zone' and distance between two UAVs in the vertical plane

4 Method of the Multi-UAV Formation Flight Control

In order to apply this approach it is required to transfer the real world properties of UAVs and their position coordinates to the virtual world with its synergetic properties, with the potential conflicts that may occur on the flight path being taken into account. [12-13].

This process includes the following steps:

- structural and parametric synthesis of the virtual world;
- structure formation and parameters of virtual measuring systems that provide conflict free trajectories calculation.

UAVs are transferred from real to virtual world as dynamic objects, with mass, attraction and repulsion potentials values being assigned to them. So, the equilibrium state can be represented as:

$$F^{+}(m_i, m_j, G, r_{cr}^{\alpha}) = F^{-}(m_i, m_j, G, r_{cr}^{\beta}) \quad (4)$$

where m_i, m_j – masses of *i*-th and *j*-th dynamic bodies, *G* – gravitational constant,

Attraction and repulsion forces can be calculated as:

$$F_{ij}^{+} = \frac{G m_i m_j}{r_{ij}^{\alpha}}; \qquad \alpha \in \{2, 3, \ldots\}; \quad (5)$$

$$F_{ij}^{-} = \frac{G m_i m_j r_{\text{кр}}}{r_{ij}^{\beta}}; \qquad \beta \in \{3, 4, \ldots\}; \quad (6)$$

Projections of attraction and repulsion forces between *i*-th and *j*-th bodies on axes *X* and *Y* are calculated by the formulas:

$$F_{ijx}^{+} = F_{ij}^{+}\frac{|x_i - x_j|}{r_{ij}} \qquad F_{ijx}^{-} = F_{ij}^{-}\frac{|x_i - x_j|}{r_{ij}} \quad (7)$$

$$F_{ijy}^{+} = F_{ij}^{+}\frac{|y_i - y_j|}{r_{ij}} \qquad F_{ijy}^{-} = F_{ij}^{-}\frac{|y_i - y_j|}{r_{ij}} \quad (8)$$

$$r_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \quad (9)$$

In equations (5) and (6), the aggregate state of the environment of the virtual world (solid, liquid, gas) is chosen by the ratio *α/β*, which characterizes the degree of self-organization of the dynamic objects. Analogy of the aggregate state of a virtual environment can serve as an aggregate state of matter - gaseous, liquid, crystalline, etc.

The resultant vector at each point of dynamic object location consists of the sum of attraction and repulsion forces $F_{ij}^{+} + F_{ij}^{-}$, but can perform a group formation, so to produce dynamic objects movement there should be present one more force which takes into account thrust force P_{ijx}, P_{ijy} direction with projection on axes *X* and *Y* (Fig. 4):

$$\mathrm{F_{ijx}} = \mathrm{F_{ijx}^{+}} + \mathrm{F_{ijx}^{-}} + P_{ijx} \tag{10}$$

$$\mathrm{F_{ijy}} = \mathrm{F_{ijy}^{+}} + \mathrm{F_{ijy}^{-}} + P_{ijy} \tag{11}$$

$$\mathrm{F_{ij}} = \mathrm{F_{ij}^{+}} + \mathrm{F_{ij}^{-}} + P_i(\chi_i) \tag{12}$$

The main condition for dynamic object motion should be satisfied in the following way: $F_{ij}^{+} + F_{ij}^{-} < P(\chi_i)$. The group consists of *n* dynamic objects and each of them can be described by the system of equations:

$$\frac{d^2 x_i}{dt^2} = \frac{1}{m_i} \sum_{i \neq j}^{n} (\mathrm{F_{ijx}^{+}} - \mathrm{F_{ijx}^{-}} + P_{ijx}) \tag{13}$$

$$\frac{d^2 y_i}{dt^2} = \frac{1}{m_i} \sum_{i \neq j}^{n} (\mathrm{F_{ijy}^{+}} - \mathrm{F_{ijy}^{-}} + P_{ijy}) \tag{14}$$

$$i \in n, j \in n.$$

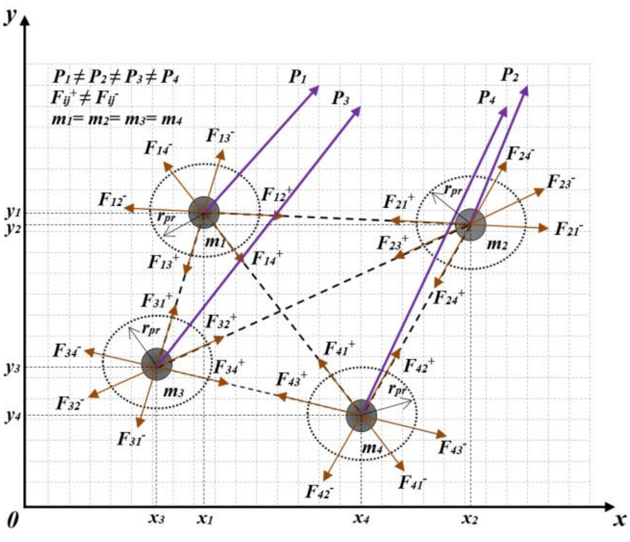

Fig. 4. The scheme of forces with four dynamic objects in the original position

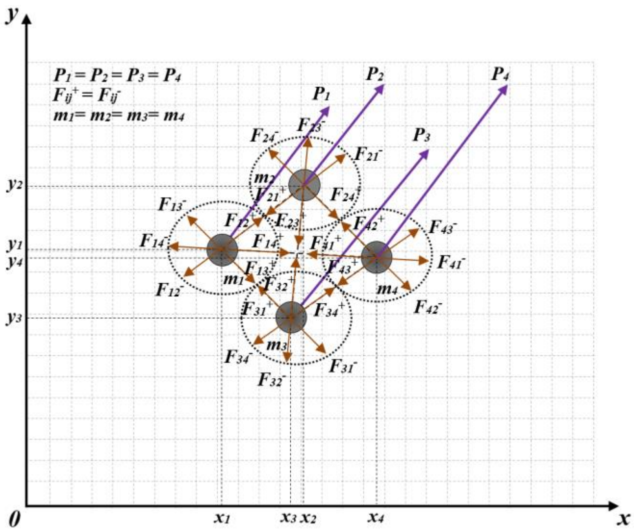

Fig. 5. The scheme of forces with four dynamic objects after group formation

The main advantage of the virtual world that was formed is that when the dynamic objects approach the critical distance r_{pr}, the resultant force acting on them is zero, i.e. the forces of attraction and repulsion balance each other. Thus, r_{pr} allows to set the size of the dynamic objects protection zone.

$$\mathrm{F}_{\mathrm{ij}}^{+} = \mathrm{F}_{\mathrm{ij}}^{-} \tag{15}$$

The absence of intersections of such zones, taking into account the uncertainty of the forecasted position of the dynamic objects, allows maintaining a guaranteed level of traffic safety in the multi-UAV formation flight control (Fig. 5).

If a static obstacle occurs on a multi-UAV path, the group interacts with it through applying attraction F_O^+ and repulsion F_O^- forces (Fig. 6). This type of maneuver can be conducted provided F_O^- is neglected, because the obstacle is static:

$$F_O^+ < \mathrm{F}_{\mathrm{ij}}^{+} + \mathrm{F}_{\mathrm{ij}}^{-} + P_i(\chi_i) \tag{16}$$

The values of heading angle χ_i and ground speed V_i may change depending on dynamic objects location relative to the obstacle and destination point.

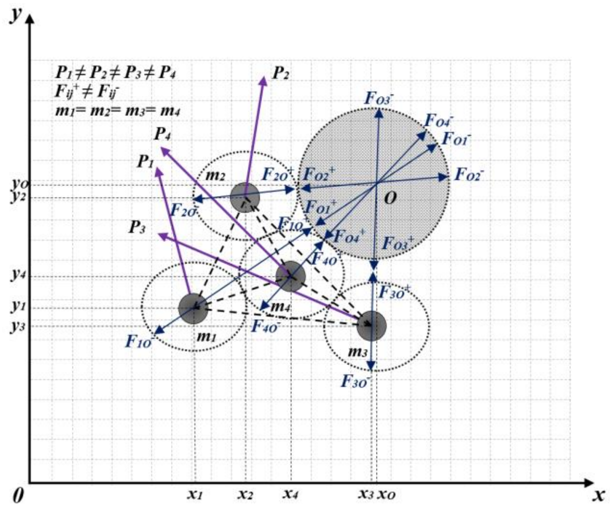

Fig. 6. The scheme of forces with four dynamic objects in a group avoiding an obstacle

5 The Multi-UAV Formation Flight Control Simulation

In order to find out if the potential field approach can be applied in the solution of the problem of multi-UAV formation flight control, Matlab simulators were used. All in all, 2 cases were simulated with a different number of dynamic objects, with UAV being referred to as a dynamic object. In Experiment 1 (see Fig. 7), 8 dynamic objects were considered with the point-mass of 1 kg and protection radius 3 m, with only one 6 m-radius obstacle to overcome. In Experiment 2 (see Fig. 8), 12 dynamic objects were considered whose point-mass was 1 kg and protection radius was 3 m, with three obstacles in the way whose radii varied from 3.5 to 4.5 m. The path was divided into 3 main stages of flight: 1) group formation; 2) obstacle avoidance; 3) straight line flight in a group to the destination. Figures represent dynamic objects movement trajectory (a), distance between moving dynamic objects, with dotted line showing protection zone with radius 3 m (b), heading angle χ_i (c) and change in ground speed V_i (d).

$$\tan\chi_i = \frac{\dot{y}_i}{\dot{x}_i} \text{ or } \tan\chi_i = \frac{\mathrm{F_{ijy}}}{\mathrm{F_{ijx}}} \tag{17}$$

$$V_i = \sqrt{\dot{x}_i + \dot{y}_i} \tag{18}$$

The dynamic objects are in their original positions with the starting speed being equal to zero. At the first stage of modelling, due to the action of attraction (5) and repulsion (6) forces the process of group formation begins, which depends on the distance between them (9). Heading angle χ_i has the same direction as vector F_{ij}, which is projected on axes X (10), Y (11) and is formed by their sum, including thrust force (12). At the same time, the shape of group formation is regulated be the equilibrium state (4), (15).

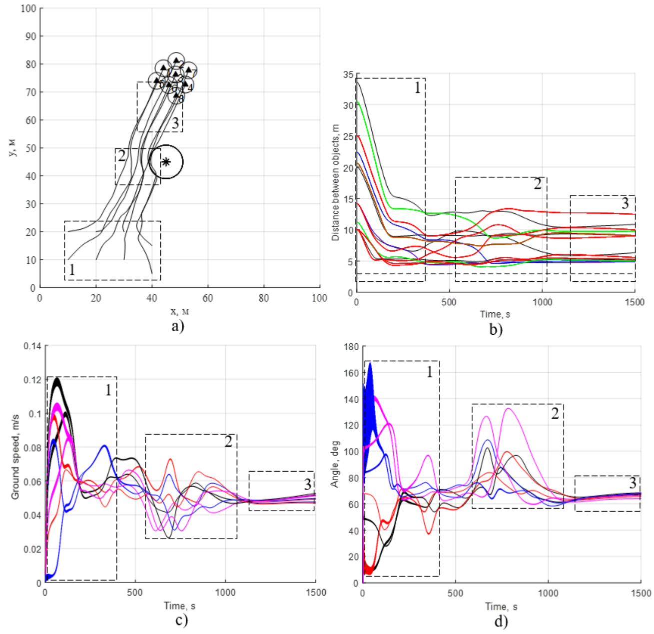

Fig. 7. Experiment 1: a) trajectory of movement; b) distance between objects; c) ground speed; d) heading angles

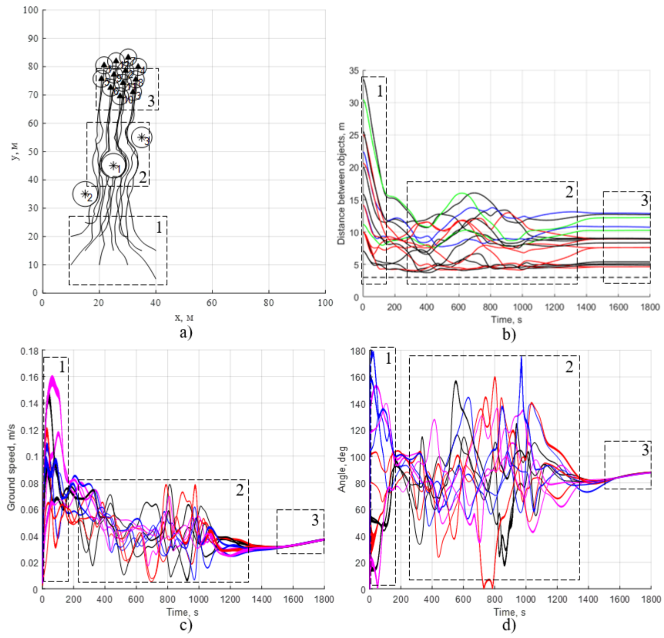

Fig. 8. Experiment 1: a) the trajectory of movement; b) the distance between objects; c) ground speed; d) heading angles

6 Conclusions

1. UAVs are widely used in different areas of human activity, and multi-UAV performance has many advantages compared with the performance of an individual UAV. Research institutions and groups are currently developing an algorithm for a group of UAV autonomous control since manual control is not available.

2. For multi-UAV formation control, the artificial potential field approach is used, where UAVs are denoted as interacting dynamic objects influenced by attraction and repulsion forces. The movement of each dynamic object is described by a system of equations, with the direction of movement coinciding with thrust force angle projected on each of axes.

3. To check the potential field approach applicability, two simulations were performed for 8 and 12 dynamic objects. The tasks were to form a group, avoid obstacles, and continue movement in the given direction with no change in the shape of the group. The results show that in this form the approach can be applied to a group formation and multi-UAV flight control. All dynamic objects moved within the allowable range determined by heading angle χ_i and ground speed V_i keeping within protection zones.

References

1. Boucher, P.: Domesticating the Drone: The Demilitarisation of Unmanned Aircraft for Civil Markets. Science and Engineering Ethics 21, 1393-1412 (2015).
2. Kuchar, J. K., & Yang, L. C.: A Review of Conflict Detection and Resolution Modeling Methods. IEEE Transactions on Intelligent Transportation Systems 1(4), 179-189 (2000).
3. Murray, R. M.: Recent Research in Cooperative Control of Multivehicle Systems. Journal of Dynamic Systems, Measurement, and Control 129(5), 571-598 (2007).
4. Geser, A., Muñoz, C.: A Geometric Approach to Strategic Conflict Detection and Resolution. In: Proceedings of the 21st Digital Avionics Systems Conference, vol. 1, pp. 6B1-1-6B1-11, Irvine, CA, USA (2002).
5. Park, J.-W., Oh, H., Tahk, M.-J.: UAV collision avoidance based on geometric approach. In: Proceedings of the 2008 SICE Annual Conference, pp. 2122 – 2126, Tokyo, (2008).
6. Matsuno, Y., Tsuchiya, T.: Probabilistic Conflict Detection in the Presence of Uncertainty. In: Electronic Navigation Research Institute (eds) Air Traffic Management and Systems. Lecture Notes in Electrical Engineering, vol 290, pp. 17-33 (2014).
7. Borrelli, F., Subramanian, D., Raghunathan. A., Biegler, L.: MILP and NLP techniques for centralized trajectory planning of multiple unmanned air vehicles. In: Proceedings American Control Conference, pp. 5763–5768, Minneapolis, USA (2006).
8. Chepizhenko, V.: Energy-potential method of dynamic objects polyconflicts guaranteed collision resolution. Cybernetics and computer engineering 168, 80-87 (2012).
9. Leonard, N., Fiorelli, E.: Virtual leaders, artificial potentials and coordinated control of groups. In: Proceedings of the 40th IEEE Conference on Decision and Control, vol. 3, pp. 2968-2973, Orlando, USA (2001).
10. Nguyen, B., Chuang, Y.-L., Tung, D., Hsieh, Ch., Jin, Zh., Shi, L., Marthaler, D., Bertozzi, A., Murray, R. M.: Virtual attractive-repulsive potentials for cooperative control of second order dynamic vehicles on the Caltech MVWT. In: Proceedings of the American Control Conference, vol. 2, pp. 1084-1089, Portland, USA (2005).

11. Xue, R., Cai, G.: Formation Flight Control of Multi-UAV System with Communication Constraints. Journal of Aerospace Technology and Management 8(2), 203-210 (2016).
12. Pavlova, S.V., Pavlov, V.V., Chepizhenko, V.I.: Virtual Einstein force fields in synergy of navigation environment of difficult ergatic systems. Proceedings of the National Aviation University 3, 15–27 (2012).
13. Chepizhenko, V.I.: Synthesis of artificial gravitational fields virtual meters for the poly-conflicts resolution in the aeronavigation environment. Proceedings of the National Aviation University 2, 60–69 (2012).