АВІАЦІЙНА ТА РАКЕТНО-КОСМІЧНА ТЕХНІКА

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Skyrda I.I.
National Aviation University

THE BEHAVIOR-BASED APPROACH FOR REMOTELY PILOTED AIRCRAFT SWARM CONTROL IN DYNAMIC ENVIRONMENT

This paper presents an algorithm for remotely piloted aircraft (RPA) swarm control applying Modified Artificial Potential Field (MAPF) approach. It is a complicated control problem, which requires developing a quick and robust system, in order to avoid collision between RPA and obstacles or RPA pairs. The MAPF use has such advantages as optimization with minimal cost, robustness that considers the global traffic condition, scalability that possesses explicit coordinates of waypoints and efficiency in implementing various tests of tuning parameters. This behavior-based approach means that each RPA shows several behaviors based on sensory inputs such as obstacle avoidance, destination tracking and swarm keeping where final control is derived from the weighting of the relative importance of each behavior. The main advantage of this approach is that it can operate in the unknown and dynamic environment because it is a parallel, real-time and distributed method, requiring less information sharing.

Key words: *remotely piloted aircraft swarm, modified artificial potential field, collision avoidance, attraction and repulsion forces, behavior-based approach.*

Introduction. To control the flight of Remotely Piloted Aircraft (RPA) swarm is a challenge as RPA are widely used in different domains. The RPA operation is effectively enhanced through the cooperation among them and make great impact on productivity in missions such as search and rescue, surveillance, mapping. Collision avoidance is central to the RPA swarm flight research. In order to avoid collision between RPA and obstacles or RPA pairs, it is required to consider the methods for formation switching and collision avoidance (Figure 1).

Classical path planning methods, such as potential field method, genetic algorithm, grid-based method and geometric approach are applied to single RPA collision avoidance. Due to the shortcomings of the traditional artificial potential field (APF) method, the Modified Artificial Potential Field (MAPF) method is developed in a certain constraint reference frame to decouple the decomposed force from the MAPF method with specific physical constraints. In the constraint reference frame, the path is examined with the updated force of the MAPF method, implemented by the RPA, and corrected if the updated force disagrees with the physical constraints.

This collision avoidance manoeuver has such advantages as optimization with minimal cost, robustness that considers the global traffic condition, scalability that possesses explicit coordinates of way-

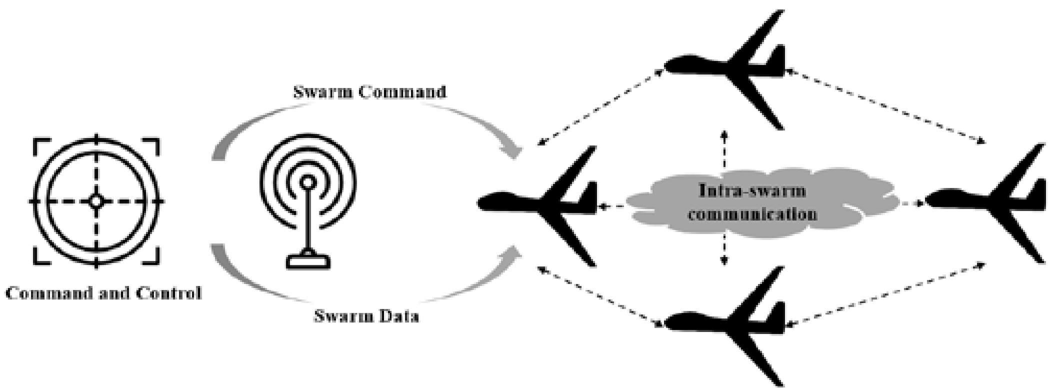


Figure 1. The scheme of RPA swarm operation

points and efficiency in implementing various tests of tuning parameters. For RPA swarm, it is necessary to consider their formation flight and collision avoidance simultaneously. Without taking into consideration the correlation between RPA, the collision avoidance method often works in a static structured environment and was not directly applied to the collision avoidance of formation flight [1, p. 2].

Related work. In the case of swarm control, RPA need to communicate with each other; therefore, information sharing plays a vital role in the overall operation. The challenge here is to make these two operations, i.e. sensing and information sharing, autonomous to achieve desired control. Autonomous RPA operation in a swarm is connected with the problems of collaboration between RPA in dynamic environment. The solution of these problems are already represented by three approaches represented on a Figure 2 [2, p. 2].

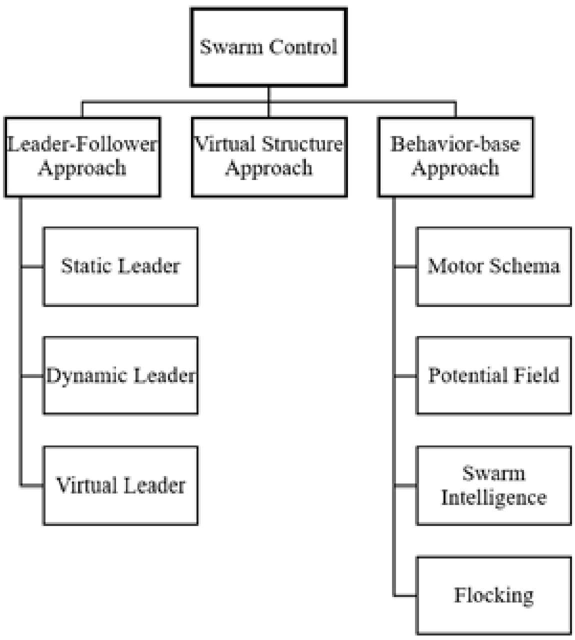


Figure 2. The swarm control method classification

In the leader-follower approach, a leader is assigned to the swarm participant and remaining members of swarm are the followers. In this approach, a leader follows its desired trajectory while follower objects track the position of the leader. There are three kinds of leader in this approach, namely static leader, dynamic leader and virtual leader. The advantage of this approach is the reduced tracking errors and can be analyzed using standard control techniques [3, p. 82]. Another benefit is that only the leader is responsible for planning trajectories and followers must follow the coordinates of the leader; therefore, it results in a simple controller. In terms of disadvantage, a leader's fault can neutralize the whole swarm and feedback from followers to a leader is generally not applied in this approach.

In the behavior-based approach, each individual swarm member shows several behaviors based on sensory inputs such as obstacle avoidance, goal seeking and formation keeping where final control is derived from the weighting of the relative importance of each behavior. There are main four methods in this approach, namely motor scheme, potential field, swarm intelligence and flocking. This approach can be defined as a structured network of such interacting behaviors where the final action of each object is derived by the behavior coordinator. The behavior coordinator multiplies the output of each behavior by its relative weight, then summing and normalizing the results. One advantage of this approach is that it can operate in the unknown and dynamic environment because it is a parallel, real-time and distributed method, requiring less information sharing [3, p. 82].

In the virtual structure approach, a virtual rigid structure is derived that represents a form of agents. Then, the desired motion of the virtual rigid structure is given, and agents' motion is derived from the given rigid structure. Finally, to track the agents, a tracking controller for each individual agent is derived in which the formation is maintained by minimizing the error between the virtual structure and the current agent position. In this approach, the desired trajectory is not assigned to the single agent, but it is shared by the whole formation team. In terms of advantage, this approach is easy to prescribe the coordinated behavior for the whole group [3, p. 82]. In terms of disadvantage, this approach is centralized, therefore, a single point of failure can crash the whole system. Furthermore, heavy communication and computation burden is concentrated on the centralized location, which may degrade the overall system performance [4, p. 74].

Problem statement. The collision avoidance methods can be divided into the following categories: the method of potential collision resolution based on geometrical approach. This method define control commands for avoidance maneuver according to the relative distance, speed, acceleration, angle, etc., between the RPA and obstacles, but it is difficult to apply in complex dynamic airspace. The second method is based on real-time path planning. With the development of research in this field, many path-planning approaches with significant improvement in timeliness have been proposed, such as artificial potential-field approaches, artificial heuristic approaches and sampling based path-planning approaches, etc., which can be applied to common path-planning problems in dynamic environments [5, p. 196].

In this paper, the MAPF proposed for RPA swarm control. The main problem can be divided into sub problems: obstacles detection, path planning, group formation, cooperation and data exchange between vehicles.

The traditional APF usually has problems connected with local minimums in the potential field function, which generate limitations such as:

1. No flight path between closely spaced obstacles.
2. Oscillations in the presence of obstacles.
3. Oscillations in narrow flight paths.
4. Non-reachable destination area or waypoint.

The RPA assumed as negatively charged particles and destination area as a positively charged. A repulsion force often dominates over the attraction force in scenarios containing RPA swarm causing the vehicles to never reach their destination area. Mathematical formulation of approach assumes a numerical value in each point in space and time, and whose gradient represents forces. Path planning using MAPF is based on a design of a standard attraction force function for the goal point, and repulsion force function with tunable parameters depending on shape, size and location of obstacles [6, p. 169]. At each point, the resulting potential field angle is lying along the angle of the resultant attraction and repulsion forces formulated by RPA, potential field functions considered as function of distance. The RPA motion in a dynamic environment is connected with potential conflicts presence with dynamic objects like RPA that has another speed value, shape, onboard equipment, so they cannot be compatible for position data inter-change performance. In this case, RPA should be able detect any dynamic obstacles operatively, calculate ranges and motion parameters.

Proposed approach. To solve RPA swarm flight control problem the MAPF used. The movement in general presented by kinematic equation system:

$$\dot{x}_i = f(V_i,\ \Psi_i,\ x_i);$$
$$\dot{y}_i = f(V_i,\ \Psi_i,\ y_i);$$
$$V_i \in (V_{min},\ V_{max});$$
$$\Psi_i \in (0°,\ 360°),$$

where x_i, y_i – are the coordinates of the i-th RPA; V_i – is a flight-path velocity vector of the i-th RPA; Ψ_i – angular position of the vector V_i; V_{min}, V_{max} – are the minimum and maximum permitted value of a speed of the i-th RPA. The value (module) of the velocity vector and the angle of its orientation (heading angle) are the control parameters in the kinematic model of the aircraft motion.

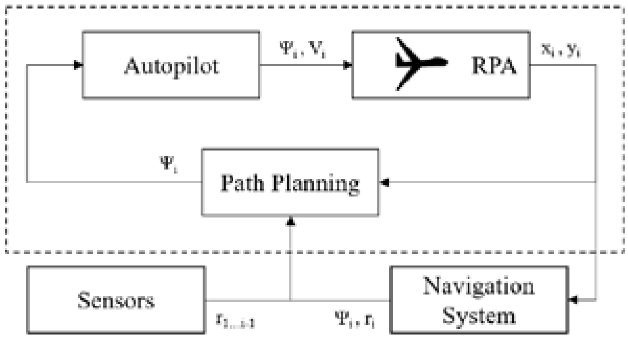


Figure 3. The RPA scheme of flight parameters processing

The RPA sensors are responsible for distances calculation between RPA and obstacles $r_{1...i-1}$ and distance to the destination r_i is provided by onboard Navigation System, also the heading to the target is provided (Figure 3). The role of Path Planning block is to define conflict free trajectory Ψ_i and Autopilot is responsible for flight trajectory correction including RPA flight performance characteristics. The result of RPA operation model will be next position coordinates:

$$x_{t+1} = x_t + v(t)\cos\Psi(t)\,\Delta t;$$
$$y_{t+1} = y_t + v(t)\cos\Psi(t)\,\Delta t.$$

This method consist in use of the real world charged particles properties to generate a force field (electric or magnetic), which at their interaction causes attraction and repulsion forces. RPA considered as the dynamic objects with the same sign and destination point has opposite sign. General character of the attraction force from the distance for different dynamic objects is qualitatively the same: the attraction force of dynamic objects to each other dominates at large distances between them and the repulsive force act at short distances r_{cr}.

$$F_{ij}^{+} = \frac{Gm_i m_j}{r_{ij}^{\alpha}}; \quad \alpha \in \{2, 3, \ldots\};$$

$$F_{ij}^{-} = \frac{Gm_i m_j r_{cr}}{r_{ij}^{\beta}}; \quad \beta \in \{3, 4, \ldots\};$$

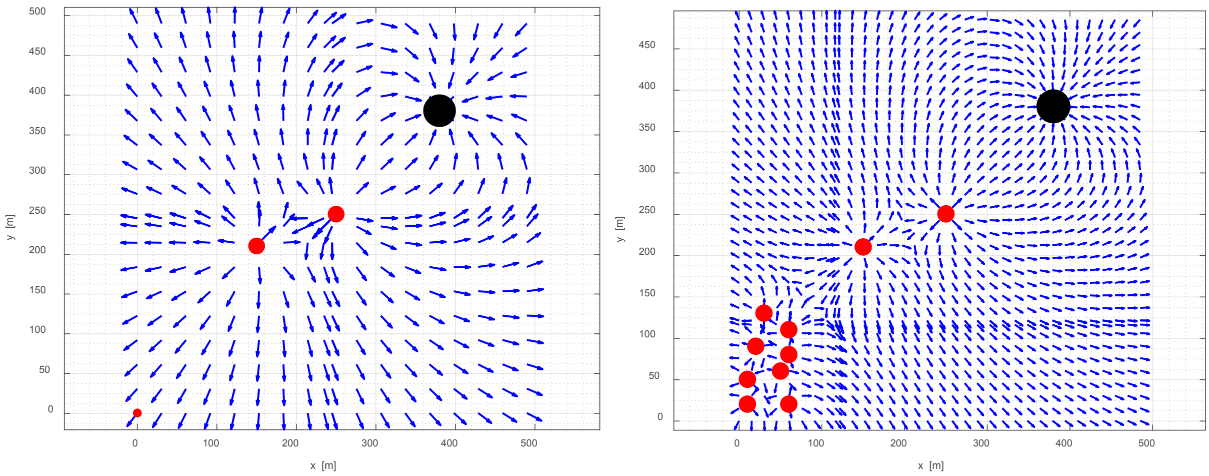
$$F_{ij} = F_{ij}^{+} + F_{ij}^{-},$$

where m_i, m_j – masses of i-th and j-th dynamic objects, G – gravitational constant and r_{ij} – distance between objects.

As a result the heading angle Ψ_i can be define as follows

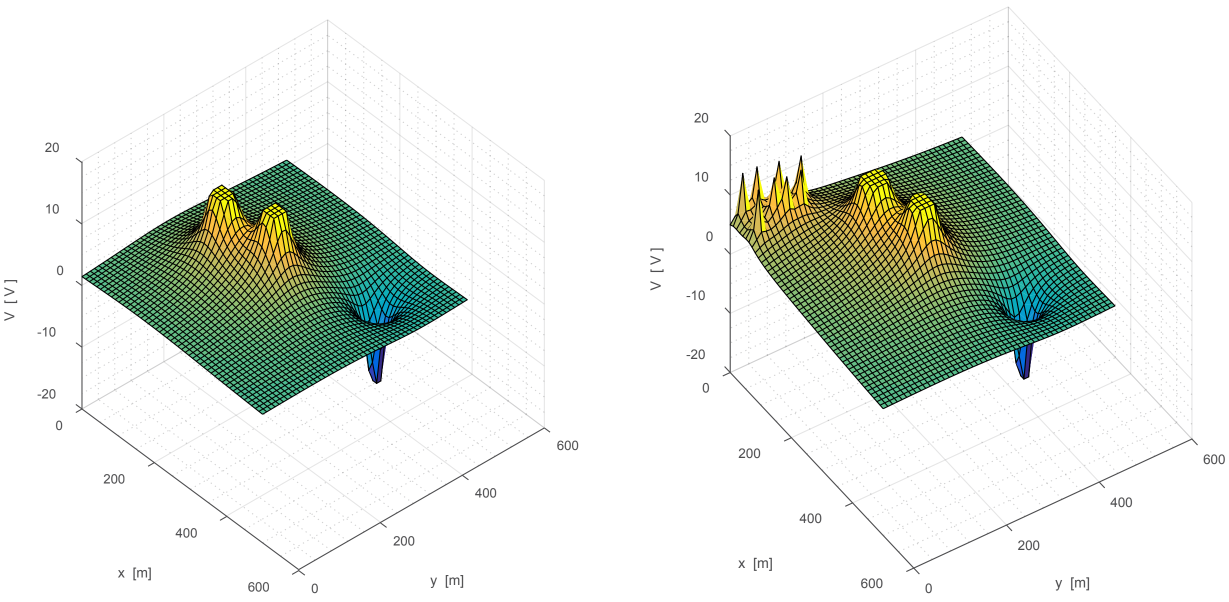
$$\tan\Psi_i = \frac{F_{ijy}}{F_{ijx}}$$

Taking into account objects positive or negative sign assignments, around each RPA the artificial force field formed.



a) b)

Figure 4. Artificial Potential Field formed by: a) obstacles and destinations zone; b) with 8 RPA



a) b)

Figure 5. Artificial Potential Field with minimums (minimums) and maximums (RPA & obstacles) formed by: a) obstacles and destinations zone; b) with 8 RPA

Simulation. The RPA motion in a dynamic environment is connected with potential conflicts presence with dynamic objects like RPA that has another speed value, shape, onboard equipment, so they cannot be compatible for position data interchange performance. In this case, RPA should be able detect any dynamic obstacles operatively, calculate ranges and motion parameters. The experiment was performed in order to check the method applicability. There are 8 RPA with different masses but the same security zone performed a mission to start at the initial zone, to form a swarm and reach the destination area while avoiding collisions with static obstacles. The main condition of flight performance was the uniform motion at a constant speed and absence of any data exchange between RPA about their position coordinates. On the Figure 6, the flight trajectory is presented where 2 obstacles are presented with inner circles and outer circles shows alert zone. These alert zones stimulate RPA to immediate actions for collisions avoidance and finding the optimal shortest way to destination zone.

The RPA main flight performance characteristics are maximum turn rate and angle. On the Figure 7 the heading angle Ψi of each RPA is presented, the traditional APF usually characterized by oscillations

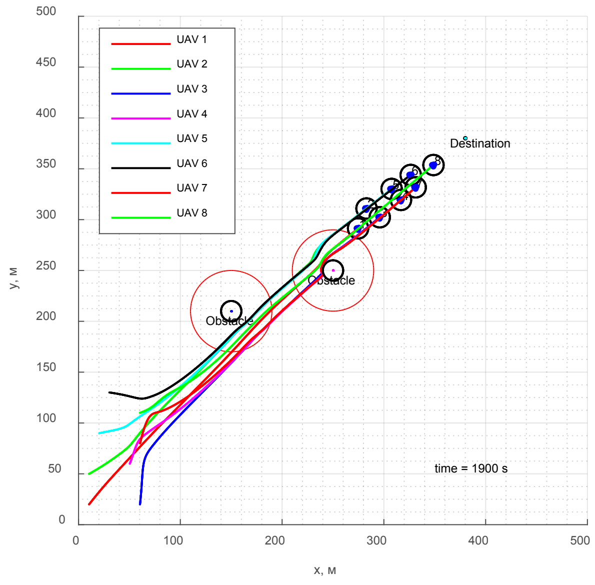


Figure 6

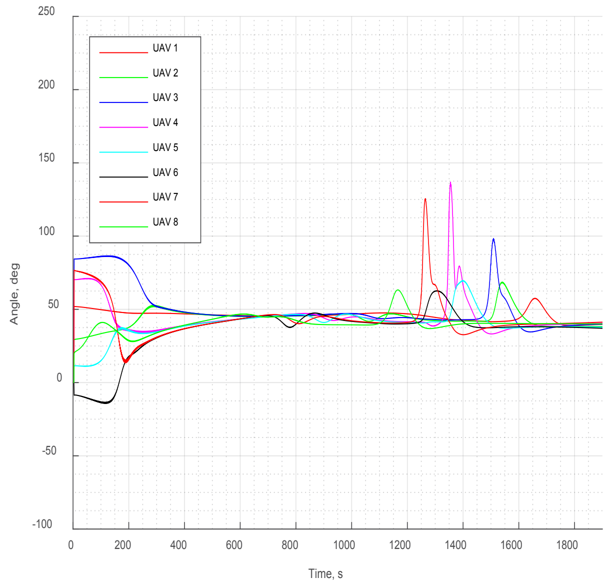


Figure 7

effects of heading value, in comparison to MAPF, which corresponds to RPA flight characteristics.

Conclusions. In this paper, the Modified Artificial Potential Field has been proposed to control a swarm of autonomous RPA to achieve the destination zone and maintain a given formation while avoiding collisions with obstacles. Behavior-Based Approach is more convenient for the task solutions because it does not require a high computational capability and the flying trajectory can be modified in real time when an unexpected obstacle has been detected. The MAPF approach allows for significant scalability to hundreds or thousands of RPA provide enough airspace for a safe operation in a dynamic environment with non-homogeneous vehicles types.

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ПОВЕДІНКОВИЙ ПІДХІД ДО УПРАВЛІННЯ РОЄМ ДИСТАНЦІЙНО ПІЛОТОВАНИХ ПОВІТРЯНИХ СУДЕН У ДИНАМІЧНОМУ СЕРЕДОВИЩІ

У статті представлено спосіб управління роєм дистанційно пілотованих повітряних суден (далі – ДППС) з використанням методу модифікованих штучних потенційних полів (далі – MAPF). Це завдання вимагає розроблення швидкої і надійної системи управління, щоб уникнути зіткнення між ДППС і перешкодами або парами ДППС. Використання MAPF має такі переваги, як оптимізація маршруту польоту за критерієм мінімуму відстані, надійність, що враховує умови глобального трафіку, масштабованість, яка має явні координати шляхових точок, і ефективність під час виконання різних перевірок із різними початковими даними. Цей заснований на поведінці підхід означає, що кожне ДППС *показує кілька поводжень, заснованих на вхідних даних, таких як запобігання зіткнень із перешкодами, відстеження цільової точки і утримання рою, де керуючі команди визначаються на основі зважування відносної важливості кожної поведінки. Основною перевагою цього підходу є те, що він може працювати в невідомому і динамічному середовищі, оскільки цей метод є децентралізованим і працює в режимі реального часу, що вимагає меншого обміну інформацією.*

Ключові слова: *рій дистанційного пілотованих повітряних суден, модифіковані штучні потенційні поля, запобігання зіткненням, сили притягання та відштовхування, підхід, заснований на поведінці.*

ПОВЕДЕНЧЕСКИЙ ПОДХОД К УПРАВЛЕНИЮ РОЕМ ДИСТАНЦИОННО ПИЛОТИРУЕМЫХ ВОЗДУШНЫХ СУДОВ В ДИНАМИЧЕСКОЙ СРЕДЕ

В статье представлен способ управления роем дистанционно пилотируемых воздушных судов (далее – ДПВС), с использованием метода модифицированных искусственных потенциальных полей (далее – MAPF). Это задача требует разработки быстрой и надежной системы управления, чтобы избежать столкновения между ДПВС и препятствиями или парами ДПВС. Использование MAPF имеет такие преимущества, как оптимизация маршрута полета по критерию минимума расстояния, надежность, учитывающая условия глобального трафика, масштабируемость, которая имеет явные координаты путевых точек, и эффективность при выполнении различных проверок с разными начальными данными. Этот основанный на поведении подход означает, что каждое ДПВС показывает несколько поведений, основанных на входных данных, таких как предотвращение столкновений с препятствиями, отслеживание целевой точки и удержание строения роя, где управляющие команды определяются на основе взвешивания относительной важности каждого поведения. Основным преимуществом этого подхода является то, что он может работать в неизвестной и динамической среде, поскольку этот метод является децентрализованным и работает в режиме реального времени, требующего меньшего обмена информацией.

Ключевые слова: *рой дистанционного пилотируемых воздушных судов, модифицированные искусственные потенциальные поля, предупреждение столкновений, силы притяжения и отталкивания, подход, основанный на поведении.*