Formation Control of Multiple Autonomous Fixed-Wing Unmanned Aerial Vehicles in Dynamic Environment

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Abstract. This paper presents Modified Artificial Potential Field (MAPF) approach application for decentralized formation control of multiple Unmanned Aerial Vehicles (UAVs) flying through dynamic environment. MAPF is based on Formation Potential Field (FPF) and it allows preventing mid-air collisions within defined security zone around multiple UAVs. This technique combines issue resolution connected with oscillation effects produced by potential fields, UAV fixed-wing type specification with the respect to application in the dynamic environment. Based on measured ranges between Remotely Piloted Aircraft (RPA) and obstacles (buildings, restricted areas), attraction and repulsion forces are formulated and are converted to aircraft flight control commands via rudder, aileron trims and engine throttle. The simulation results are used to validate and verify a given approach of real application, provision of optimal, collision-free, and safety flight path between initial UAVs positions and destination area.

Keywords: multiple unmanned aerial vehicles, remotely piloted aircraft, artificial potential field, formation control, mid-air collision, obstacle collision avoidance, path planning, dynamic environment.

1 Introduction

Unmanned Aerial Vehicles (UAVs) are the remotely piloted aircraft (RPA), automation levels of such vehicles vary from those that are fully piloted from a remote location to fully automated. These ‘pilotless’ aircraft are developed for a big variety of applications, such as surveillance, rescue, border control, agricultural production support, etc. UAVs’ world legal acceptance is connected with their integration into the existing aviation system without negatively affecting manned aviation and infrastructure, such as mid-air collisions (MACs) – that is the main challenge today [1]. The International Civil Aviation Organization’ (ICAO) and current European Commission’ (EC) regulatory documents will only permit the autonomous maneuvers to override operator command in emergencies such as communication failure or collision risk. Multiple UAVs operations have both practical potential in different applications and theoretical challenges arising in coordination and control of the vehicles group. One of the main problems regarding to autonomous UAVs activities in a group is an ability to move between obstacles and avoid collision with them effectively, which itself includes subproblems such as obstacles detection, path planning, group formation and data exchange between vehicles.

UAVs are usually used in remote and dangerous areas, especially fixed-wing that have a high speed and heavy payload in comparison to rotary wing UAVs type. The complexity appears because of the UAVs' size is becoming smaller and as a result their weight is becoming lighter. Therefore, taking into account these properties, UAVs have not the ability of carrying heavy sensors such as Light Identification Detection and Ranging (LIDAR) [2] or radar. Hence, the suitable solution is to use the on-board cameras due to their advantage of lightweight and low power consumption.

In addition to camera's lightweight and the lower power consumption, the cameras are able to provide detailed environmental information Therefore, they are considered as the important sensors mounted on the small UAVs. The following obstacle avoidance sensors are being used in the RPAs, e.g.:

- Stereo Vision;
- Ultrasonic (Sonar);
- Time-of-Flight;
- Infrared;
- Monocular Vision.

Another issue is connected with the path planning, which consists of defining a set of paths, parameterized by time in order to accomplish a mission determined by waypoints respecting flight specifications limits of both the UAV and the environment [3]. Also, path planning for multiple UAVs requires continues data exchange between formation members, so it should take into account confounding factors such as network latency, packet loss, and the unique UAV's flight peculiarities.

The collision avoidance algorithms applied to UAVs operation can be divided into 5 main groups [4]:

1) Geometric Approach;
2) Evolutionary Algorithm Approach;
3) Grid-based Approach;
4) Mixed Integer Linear Programming Approach;
5) Artificial Potential Field Approach.

The artificial potential field method (APF) is an approach of generating trajectories online. It enables UAVs to navigate in a real condition environment with static and dynamic obstacles by avoiding them. It is widespread due to its mathematical, algorithmic simplicity and not computationally expensive [3]. This reduction in computational complexity makes the APF approach tractable for large numbers of UAVs. Moreover, because the force on each UAV is calculated independently, the problem could potentially be distributed onto flight management systems aboard each of the UAVs, which further reduces the computational burden on any single machine. Additionally, since the UAVs operate independently, uncooperative aircraft in the airspace can be handled without issues [5].

2 Related Work

The first approach proposed for collision avoidance based on artificial potential field (APF) application was developed by Khatib [6]. The paper presented the process of mobile robots movement to the goal position with one obstacle under the action attraction force produced by the destination point and artificial repulsion force created by the obstacle surface. The main drawback of such classic approach connects with the calculation of local minima in case of the presence more than one obstacle. L. Wang, K. Chen, and Y.S. Ong [4] proposed to eliminate such effect by decomposing a complex problem into a set of simple one (subgoals) with grid-world environment dynamically and automatically, but the resultant paths are not the optimal solutions. In [7] this work the authors tried to apply APF for helicopter type UAVs formation flight control with a virtual leader of the group and extended version of the potential field solution. The reason for this was a swarm constellation instability during an obstacle and collision avoidance. It is not applicable in case of fixed-wing UAVs operation because of flight features (velocity limits, unable to hover). The main task of tradition APF is connected with a centralized control scheme required to have either ground control station or virtual leader, so it directly influences on a reliability level in case of failure, and does not guarantee the effectiveness in a dynamic, unknown environment. The robust swarm control strategy for multiple UAVs operation in uncertainties conditions and varying mission environment have been proposed by K. Han, J. Lee, and Y. Kim [8]. The swarm should perform highly coordinated movements when the UAVs meet the pop-up threats. It is realized through assignment swarm geometry center and behavior set of rules, e.g.: avoidance rule, velocity matching rule, flock center rule. The resultant vector is used in the rules represented as a gradient vector, composed of attractive and repulsive potential functions. The UAVs must deal with a constant movement and limited turning ability, which make a collision avoidance more complicated, especially in the case of collision avoidance with dynamic obstacles in a limited airspace. The work done in [5] using APF minimize the number of potential collisions and the amount of required maneuvers to avoid other UAVs in a way.

P. Vadakkepat, K. Chen Tan and W. Ming-Liang [9] proposed an evolutionary artificial potential field (EAPF) approach for a real time path planning composed of artificial potential field method and artificial intelligence combination. In comparison to traditional APF, where an obstacle is considered as a point of highest potential, and a goal as a point of the lowest potential, vehicle moves from a high potential point to a low potential one, EAPF method uses the multi-objective evolutionary algorithms to optimize the potential field functions.

H. Yin, L. L. Cam, U. Roy [10] outlined two main drawbacks of APF approaches for multiple UAVs formation control proposed earlier. First, the gradients at some specific points of field may not exist due to the presence of global attractive potential and has a disrupting effect on the smoothness of the whole potential field. Second, the method can still fail to achieve its goal when agents are not well distributed around the formation area in other words UAVs can't find the way to the target position since the influence of a local attractive potential has been blocked by other vehicles. Modified Artificial Potential Field (MAPF) [10] excludes these disadvantages by application Formation Potential Field (FPF) [11] and avoids situations where other repulsive potential field neutralizes the attractions of the target attractive potential field when it should not, simultaneously a potential function is divided into global and local.

3 Problem Statement

The global purpose of this research is to create an algorithm that guarantees safe flight generation and collisions avoidance for autonomous UAVs operation without human controlling within a limited airspace.

The main requirement is to handle collisions with fixed-wing UAVs that move at a constant speed (cruise speed, V_{cruise}) because of low energy consumption.

The effectiveness will be evaluated as a possibility to avoid potential collisions and conflicts, at maximum turn rate with correspondent velocity value (V_{turn}), occurred on the way and guarantee destination zone achievement. Potential collision is characterized by inner protection zone (r_{min}) intersection with an obstacle and conflict – outer protection zone (r_{max}) (Fig. 1). The sizes will be represented in a timely manner, for small UAV (with a weight that does not exceed 20 kg) it may be t_{min}=5 and t_{max}=10 seconds correspondently.

$$r_{min} = V_{turn} \times t_{min}; \quad (1)$$
$$r_{max} = V_{cruise} \times t_{max}; \quad (2)$$

These values satisfy next conditions: minimum number of collisions and maneuvers, UAV-to-UAV communication network latency, packet loss, obstacles detection range, unique UAV flight specifications depending on size or payload.

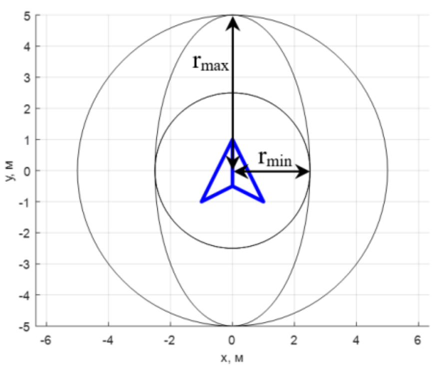


Fig. 1. UAV protection zone, inner circle corresponds to maximum turn rate in few seconds and outer circle characterized by cruise speed

The algorithm tests will be done using a simulator, which has such advantages: to allow finding the maximum number of UAVs safely operates in limited airspace, to model ideal conditions without unforeseen environmental factors and, in opposite side, with weather or technical factors influences. The main issues are connected with wireless communication between UAVs in a group. For this case, there is a lot of technologies for short-range line-of-sight (LoS) links deployment, which are flexibly configured and can be installed fast. The important criteria, which influence on communication link type, are data exchange rate, physical size and energy consumption. In general, UAVs supposed to be used in remote areas without a ground control station coverage, for example, in cases of severe shadowing by urban or mountains terrain, or communication infrastructure damages by natural disasters.

Artificial Potential Field method is more preferable for the solution of such issues as collision avoidance and formation control, because it is relatively simple for implementation, more efficient, fast and accurate. It assumes destination area or waypoints signed as positive charges and other dynamic objects (UAVs or obstacles) in the space as negative charges. An optimal flight path is found by calculating a total force from the attraction force of UAVs towards their destination and repulsion force away from other obstacles presented in the area (Fig. 2).

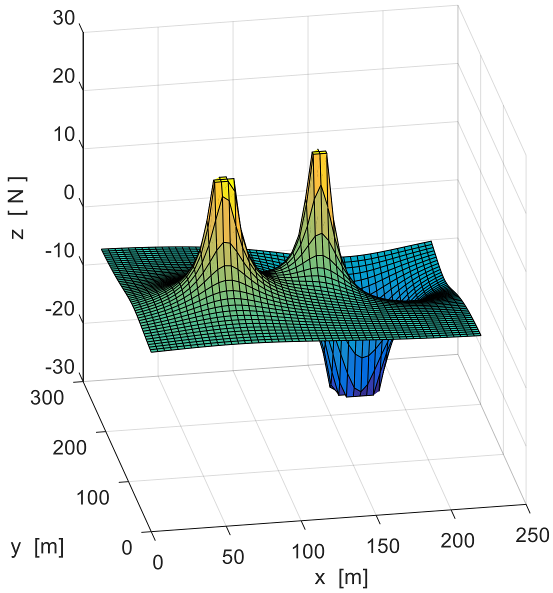


Fig. 2. Two obstacles and destination zone formulate potential field in the optimal way

However, the traditional APF usually has problems connected with local minimums in the potential field, which generate limitations such as (Fig. 3):

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.

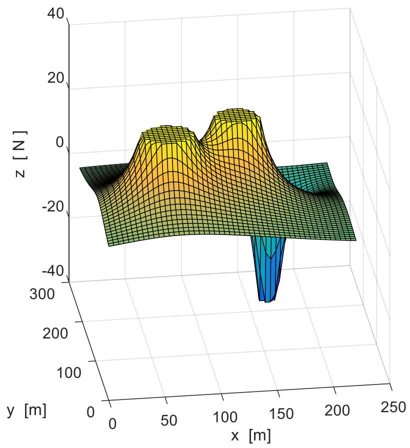


Fig. 3. Two obstacles and destination zone with high potentials formulate potential field

4 Proposed Approach

In this paper, an online (global) path-planning algorithm based on a modified APF approach is proposed for the control of UAVs swarm in dynamic environment, which causes constant collision avoidance with buildings, UAVs coordinates and position calculation errors based on Global Navigation Satellite System (GNSS), Inertial Navigation System (INS) and visual/radio sensors. The modification of the APF is for generating the shortest and safest path for the UAVs. Simulations are used to verify the proposed approach using MATLAB.

The Artificial Potential Field is one of the classical path planning approaches that is used for global and local path planning in the dynamic or static environments. The concept about APF is to find a mathematical function to represent attraction and repulsion forces acting UAVs and destination area both forces are generated by mathematical functions that are represented graphically by high and low areas in the simulated space.

We model the UAVs as negatively charged particles and destination area as a positively charged (Fig. 4). A repulsion force often dominates over the attraction force in scenarios containing multiple UAVs 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 (3).

$$F_{total} = \xi \times F^{+} + (1 - \xi) \times F^{-}; \quad (3)$$

where F_{total} is a total force acting on one UAV, F^{+} – is an attraction force, F^{-} – is a repulsion force, ξ is an attraction force weighting coefficient ($0 < \xi < 2$) which ensures attraction force domination under repulsion in order to guarantee UAV flight towards destination area (Fig. 5).

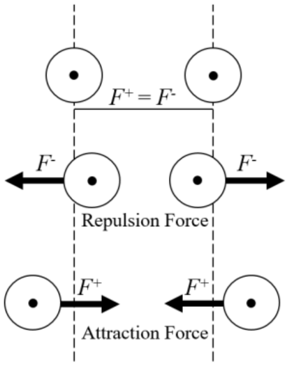


Fig. 4. Dynamic objects' interaction with different potentials

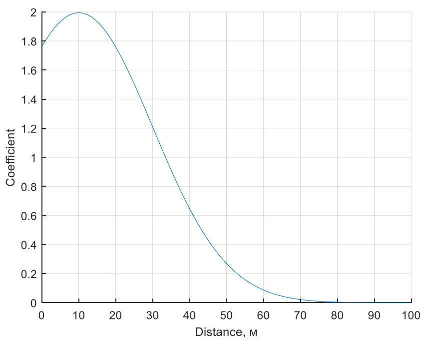


Fig. 5. Attraction force weighting coefficient dependence on distance to the destination

Oscillation effect referred to traditional effect is eliminated by changing circle to elliptical artificial potential field around UAV with the same area. It increases in a size toward the heading of UAV, indicating a flight direction (Fig. 1).

Additionally, the deadlock problem solution is presented, where at least two UAVs are approaching each other head-on with destinations directly behind each other, since UAVs cannot turn sharply or come to a complete stop to resolve this issue one UAV turn to the left or right due to the action of artificial vortex repulsion field (Fig 6). In some cases this principle is applied for collision avoidance with static obstacles [5].

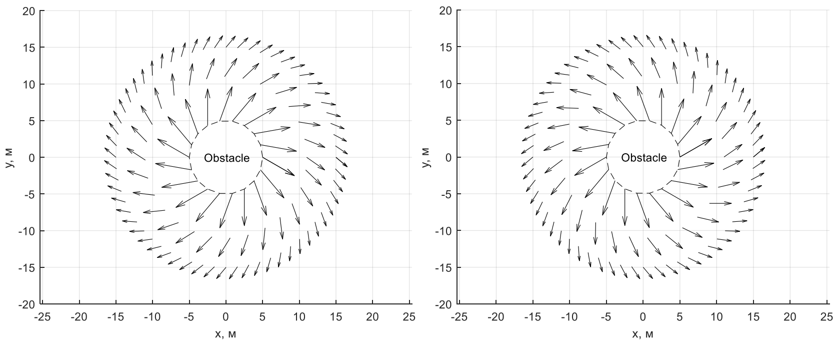


Fig. 6. Artificial vortex repulsion field is formulated around obstacle

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. At each point the resulting potential field angle is lying along the angle of the resultant attraction and repulsion forces formulated by UAVs, potential field functions considered as function of distance (Fig. 7).

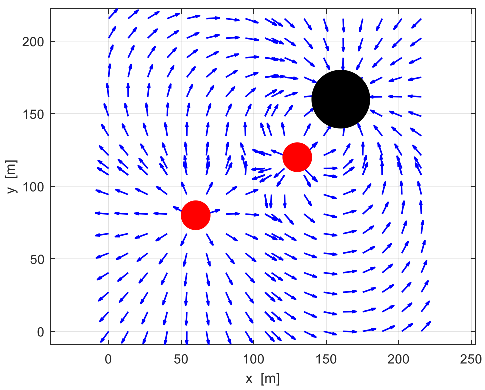


Fig. 7. Two obstacles and destination zone formulate potential field (red – obstacles, black – destination)

5 Formation Control of Multiple Autonomous Fixed-Wing Unmanned Aerial Vehicles Simulation

It is assumed that there are six UAVs, two obstacles and one destination zone for a group. The aim is to plan an optimal collision-free path for the group, in case of multiple UAVs application in a dynamic environment, where due to signal delay, multipath and close obstacle location present an error of UAV coordinates definition and cooperation in a group. The protection zone radius is equal to minimum value and remains a constant during flight. The main peculiarity of such approach in comparison to others [1, 5, 7, 8] is that a group is operated without any leader.

UAV movement can be described by kinematic equation system:

$$\frac{dx_i}{dt} = f(x_i(t), V_i(t), \varphi_i(t)); \quad (4)$$

$$\frac{dy_i}{dt} = f(y_i(t), V_i(t), \varphi_i(t)); \quad (5)$$

where, i=1, 2, …, n is the index of multiple UAV, x_i, y_i – coordinates of the i-th UAV, V_i – is a flight-path velocity vector of the i-th UAV, φ_i – is the course angle characterizing the direction of the velocity vector to the destination zone.

The UAV coordinates can be calculated as a resultant force acting on i-th UAV provided by destination zone, obstacles and other UAVs:

$$\ddot{x}_i = \frac{1}{m_i} \sum_{i \neq j}^{n} F_{xij}^{+} - F_{xij}^{-}; \quad (6)$$

$$\ddot{y}_i = \frac{1}{m_i} \sum_{i \neq j}^{n} F_{yij}^{+} - F_{yij}^{-}; \quad (7)$$

where, m_i – is a mass of the i-th UAV

Attraction F^+ and repulsion F^- forces can be calculated as:

$$F_{ij}^{+} = \frac{G m_i m_j}{r_{ij}^{\alpha}}; \qquad \alpha \in \{2, 3, \ldots\}; \quad (8)$$

$$F_{ij}^{-} = \frac{G m_i m_j r_{\text{кр}}}{r_{ij}^{\beta}}; \qquad \beta \in \{3, 4, \ldots\}; \quad (9)$$

$$\mathrm{r_{ij}} = \sqrt{(\mathrm{x_i} - \mathrm{x_j})^2 + (\mathrm{y_i} - \mathrm{y_j})^2}; \quad (10)$$

where, G – is a gravitational constant and r_{ij} – is a distance between UAV,

In order to provide the UAV movement to the destination zone, it is necessary that its attraction force should be greater than total attraction force formulated by obstacles and other UAVs [12].

The heading angle φ can be estimated as a relation of attraction and repulsion force influence on the UAV movement with correspondent coordinates.

$$\varphi_i(k) = arctg\left(\frac{\dot{y}_i}{\dot{x}_i}\right) = arctg\,\left(\frac{y_i(k) - y_i(k-1)}{x_i(k) - x_i(k-1)}\right); \quad (11)$$

where, k – is the integration step of the equation system.

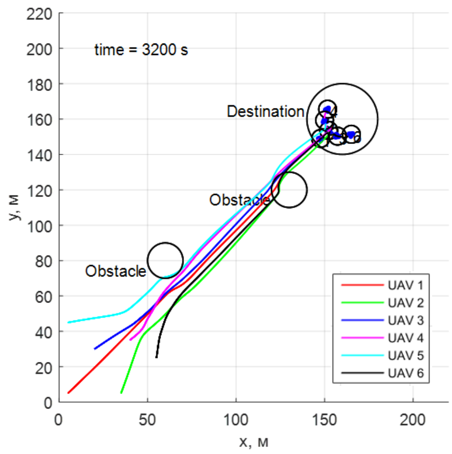


Fig. 8. Experiment 1. Flight trajectory of 6-th UAVs in a group with constant radius of protection zone

The formation control problem of UAVs group in static and dynamic environment consists of three main problems: plan, control and form a UAVs formation in a group at their initial positions; group motion from initial position to destination; collisions avoidance during the flight (Fig. 8).

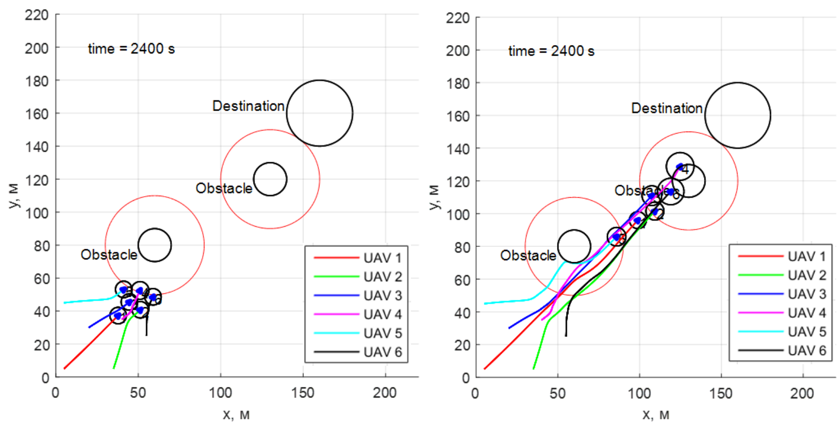


Fig. 9. Experiment 2. Flight trajectory of 6-th UAVs in a group with varying radius of protection zone

The zone around obstacles has double radius value and in case of its penetration, the UAV security zone will be increased in accordance to Fig. 1, where radius is inversely proportional to the distance between UAV and the nearest obstacle edge point of contour, because obstacles can have rather different shapes.

The results of simulation depict applicability of MAPF regarding UAVs operation in the real world with static obstacles. Experiment 2 (Fig. 9) has expensed less time to reach the destination area in comparison to Experiment 1, where UAVs trajectories, in some cases, drawing obstacle shapes. In Experiment 2 (Fig. 10) UAVs start collision avoidance maneuvers earlier and characterized by potential collisions absence.

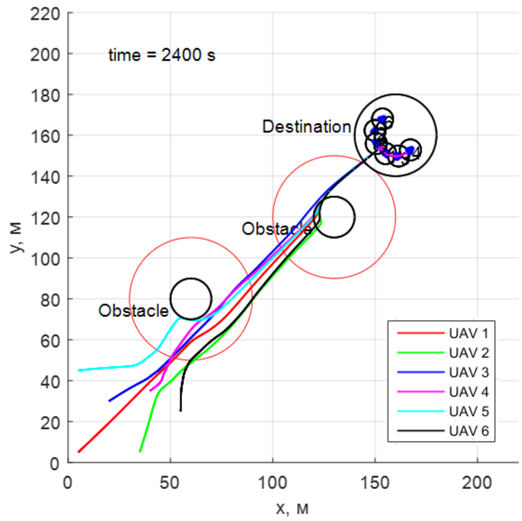
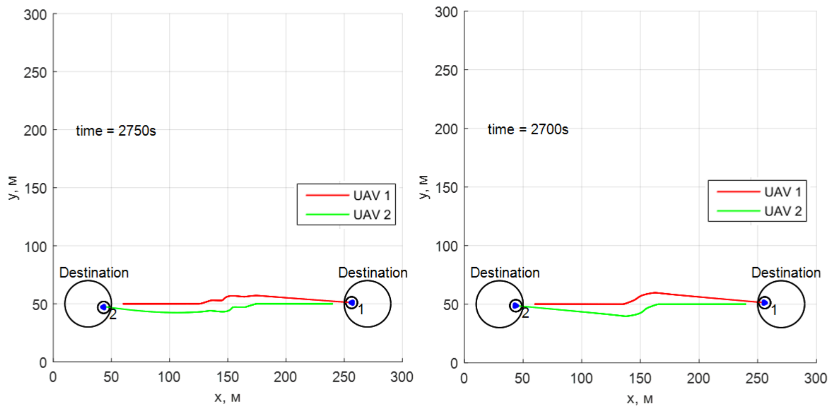


Fig. 10. Experiment 2. Destination zone is reached by 6-th UAVs in a group in 2400 seconds

The UAV motion in a dynamic environment is connected with potential conflicts presence with dynamic objects like UAV that has another speed value, shape, onboard equipment, so they can't be compatible for position data interchange performance. In this case, UAV should be able detect any dynamic obstacles operatively, calculate ranges and motion parameters. The traditional APF is characterized by dead lock problem and the solution provided by artificial vortex fields (Fig. 6) that act only around obstacles and do not make an impact on a global potential function. In order to check this Experiment 3 (Fig. 11) and Experiment 4 (Fig. 12) have been done. The main difference between them is an application of varying security zone radius. Experiment 3 shows a flight performance of two vehicles and their destination zones. In Fig. 11(b) the flight path is optimal with less time consumption and slight maneuvers.



a) b)

Fig. 11. Experiment 3. Collision avoidance with dynamic obstacle, like UAV with constant (a) and varying (b) radiuses of protection zone

Proposed MAPF has showed the best result in case of UAVs group motion in dynamic environment based on time consumption and number of flight maneuvers corresponding to lower energy consumption, it is the main issue characterized UAV operation (Fig. 12).

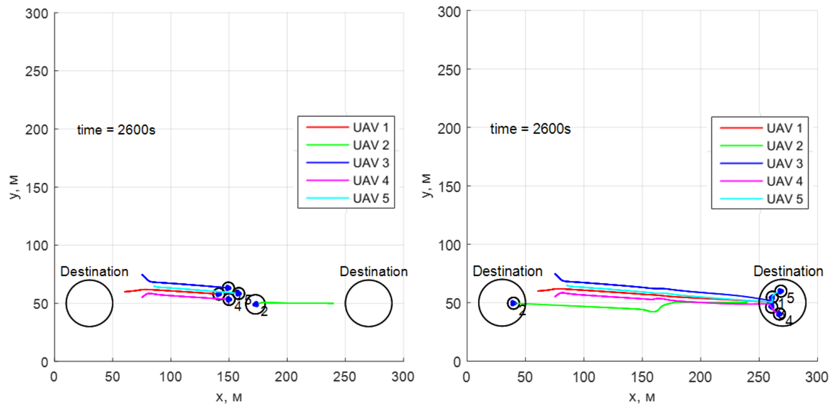


Fig. 12. Experiment 4. Collision avoidance with dynamic obstacle, like UAV with constant radius of protection zone around UAVs in a group and varying around standalone

6 Conclusions

In this paper, the Modified Artificial Potential Field has been proposed to control a group of autonomous UAVs to achieve the destination zone and maintain a given formation while avoiding collisions with static and dynamic obstacles. Unlike other centralized UAV formation control methods, the MAPF method 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 is based on application of artificial vortex fields around obstacles and varying protection zone radius of UAVs. It allows for significant scalability to hundreds or thousands of autonomous UAVs provide enough airspace for a safe operation in a dynamic environment with non homogeneous vehicles types.

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