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Establishing Obstacle and Collision Free Communication Relay for UAVs with Artificial Potential Fields

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Abstract In this paper, Unmanned Aerial Vehicles are used for establishing an airborne communication relay chain to extend the communication range or to obtain a channel between two far points which are outside the single UAV communication range. Positions of the UAVs in the chain are detected by the vehicles autonomously and while establishing the suitable formation, collision avoidance between vehicles and other geographical obstacles are considered by using artificial potential fields. Especially to provide reliable continues communication between vehicles as uninterrupted channels, positions of the UAVs which are providing line of sight, calculated automatically by tuning artificial potential field parameters dynamically. The success of this novel approach is expressed by simulation studies in Matlab environment and the simulation results are validated using NS2 simulator.

Keywords Airborne communication chain relay · Autonomous systems · Artificial potential fields · Path planning

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1 Introduction

As a result of Unmanned Aerial Vehicles (UAV) being widely used in civil and military-purposes, academic studies and researches on the autonomous capabilities of the UAVs are gaining momentum [1]. Today, UAV platforms are used especially in reconnaissance, surveillance and communications purposes [2].

Another important usage area of UAV's is to establish a reliable communication infrastructure like airborne relay chains [3]. Main reasons to need UAVs airborne communication relay chain can be explained as;

- Extending the maximum range by using multiple UAVs between land station and leader UAV which one will accomplish mission [4],
- Establishing fast, secure and dynamic communication channel between two points,
- Communicating an UAV, that is behind a physical obstacle, by establishing Beyond Line of Sight (BLOS) communications.

First of all, UAVs airborne communication relay chain can be used for extending control range of a platform. For example, the target position is far away from the base station; UAV communication range will not cover the target area. As secondary usage area of UAVs airborne communication relay chain is providing a communication channel with the target which is outside of the single UAV communication range. If UAV base far away from the target, a group of cooperative mini UAVs can establish an airborne link with the base and the target. For example, to establish the communication five UAVs will perform a cooperative work while enhancing the communication range for control and data transfer. Basic problem area for cooperative UAVs which will try to establish an airborne communication relay chain is positioning difficulties in formation. Especially in sites like which contain obstacles like mountains and/or buildings etc., it is difficult and critical task to provide a static position for each UAV in chain. The complexity of the problem will be higher when the number of UAVs in chain increases and the obstacles are unknown. To provide BLOS capabilities within an area of operations under direct control of the base station without using scarce satellite resources, a UAV communication chain can be provided to extend the range.

In Fig. 1, contour lines represent the equal altitude levels. It is assumed that all of the UAVs will fly in the same flight level during the mission in this work. Platforms fly at a fixed altitude which is applicable for the UAVs and the optimum level to communicate each other without affected by possible various obstacles [5]. Another factor to determine the flight level is maximizing the range of the chain or minimizing the number of UAVs to reach the target destination. In Fig. 1, counter lines represents equal altitude levels of the obstacles. Bold line in Fig. 1 represents the flight altitude which is defined as 1200 meters. Counter lines, drawn inside of the bold, are borders of obstacles, either blocking wireless communication or flight pattern. If UAVs are fixed wing type vehicles, they are not able to hold in a fixed point like rotor-crafts and they must have circular like pattern around a center point. While performing holding-pattern around the point, also each UAV must control the link to prevent the getting out the communication range. Beside UAVs must synchronize their holding maneuvers to reach maximum communication range.

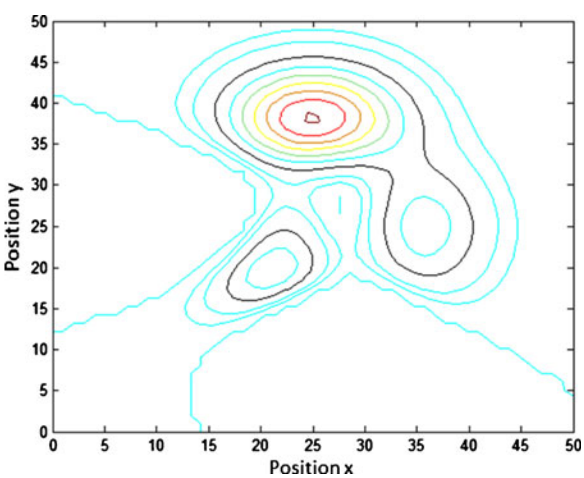

Fig. 1 2D representation of the flight area by using altitude contour lines

The approach described in this work can also be used for the purpose of transferring online captured video data of a mobile target as well as increasing the remote control range of an UAV by using cooperative UAV relay chain. In these possible applications, UAV operator is only responsible for controlling the leading UAV and managing its payload, other UAVs are in an autonomous state from takeoff to landing and are only responsible for cooperatively taking appropriate positions between the base station and the leading UAV to enable reliable continuous communication. While UAVs performing a cooperative mission as a group there are various risks like collision or obstacle crash. To provide collision or obstacle avoidance, Artificial Potential Filed (APF) approach which is one of the techniques in robotic applications is used [6].

The major concepts of providing an airborne communication relay can be list as;

- Positions of the UAVs must be determined autonomously by themselves,
- Relay chain always must be retained to be able to communicate with frontiers and the source station,

- Physical and environmental factors will try to broke the communication chain, each vehicle continuously update its position taking into account the location of its neighbors autonomously,
- Vehicles always stay in Line of Sight (LOS) with at least one other,
- Autonomous collision avoidance is critical especially in narrowed parts of terrain,
- During clearance of above constraints, UAVs must also autonomously avoid obstacles like mountains which are over flight level.

As described in the above list, there are numerous factors in providing continues manner reliable communication airborne link. To manually provide this kind of task can be hard to implement and caries various risks like losing communication or worse vehicle crashes.

In the following section, we mention about related works; APF design and establishing a communication chain relay by using UAVs in an obstacle free area especially for high altitudes and long ranges [3, 6]. In Section 3, the model of the geographical obstacles definitions with APF models are explained. In Section 4, LOS formulation and the effects on the positions of the UAVs are handled. In Section 5, the entire model of the work is defined. Section 6 describes the success of the approach with the results of the simulation works. Finally, conclusions and desired future work is mentioned.

2 Artificial Potential Field Based Path Planning

A number of various approaches for robot navigation have been proposed in literature [8]. However, practical solutions have some serious drawbacks like imprecision of measured data, absence of complete knowledge about environment and computational complexity. Because of its easy modeling opportunities, simple and also flexible architectures, APF based navigation approach is very popular for robotic applications [9]. APFs are one of most common techniques to plan paths to a goal while avoiding obstacles. In APF, there are two types of obstacle definition; static obstacles like geographical obstacles (mountains, valleys etc.) and dynamical obstacles like other vehicles and defined obstacles which are repulsive forces and the target is the attractive force. The attractive points which represent the sinks; and the repulsive points which represent the hills; are measurable values and they depend on basic functions, flexible and effective definitions. An algorithm and structure can be achieved by separating the components of these measurable values to reach the target point in a pattern.

APF is one of the common techniques to define the track which aims to reach target point by avoiding obstacles. The first example of such a potential field method was proposed by Khatib inearly 80's [10]. In this approach, force control is achieved by gradient of the attractive and repulsive fields. Kodisteck shows that an APF can be designed by using some special parameters for a mobile robot which provides always to go to the real target point without effecting local minimums [11]. Combination of global and local path planning by using APF is demonstrated by Krough and Thorpe [12] and application of APF for the robots which have real time sensors are improved by Brooks [13] and Arkin [14]. Producing vector fields by combining APF and grids is applied by Borenstein [15]. Connolly aims to develop a path planning algorithm for mobile robots which depends on APF [16]. APF based path planning approaches which are not containing local minimum points are developed by using static fields. Ahmad has generalized APF based navigation in an area which has known static obstacles [17].

$$f(x, y) = -\log\left(\alpha\left((x - x_a)^2 + \gamma\,(y - y_a)^2\right)\right) \quad (1)$$

In this work, harmonic function which is defining in Eq. 1 is used to generate the APF. The same function is used for defining the attractive potential field and repulsive potential fields. The most important property of harmonic functions is that they are independent from local minima [7] as shown in Figs. 2 and 3.

Equation 1 produces spherical symmetry form potential field which is changing according to the "γ" variable's value. If $\gamma = 1$ then the equation result becomes a circle form potential field, for the other values of "γ" it will be in ellipse form.

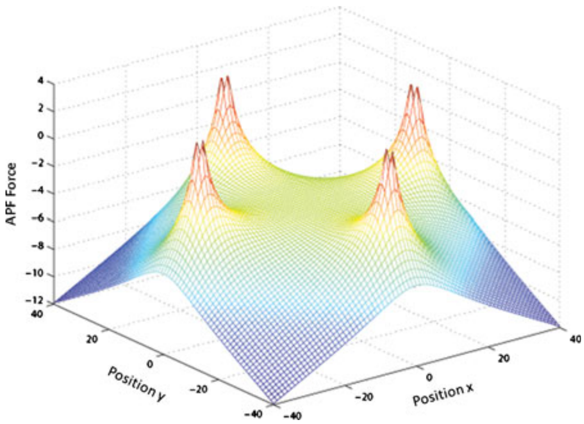

Fig. 2 Three obstacle demonstration with harmonic potential functions in APF

The center of the field will be the point which is defining with (x_a, y_a) parameters. "α" is the magnitude factor of the potential fields. This "α" factor will be very big number in attractive field relatively to the value in the repulsive field.

The target point, which vehicle tries to reach, is a kind of center point of the attractive field and the obstacles which vehicle tries to avoid while going to target point, are the center points of the repulsive fields in the same coordinate system.

By calculating the gradient of the sum attractive and repulsive fields, every force of the point in the area can be achieved. The equations which are using for the calculation of total gradient in two dimensions can be seen in Eqs. 2 and 3.

$$d_x = 2(x - x_a) \big/ \left((x - x_a)^2 + \gamma\,(y - y_a)^2\right) \tag{2}$$

$$d_y = 2\gamma(y - y_a) \big/ \left((x - x_a)^2 + \gamma\,(y - y_a)^2\right) \tag{3}$$

3 Airborne Communication Relay Approach

In order to achieve continuous long-range communication relay infrastructure, APF based path planning of UAVs is discussed and a novel dynamic approach to relay-chain concept is proposed to maintain the communication between vehicles [3]. Furthermore, keeping vehicles in communication range dynamically and appropriate position to maintain continuous relay formation, APF based path planning technique is used and also it provides collision avoidance system for the vehicles each other. Continues state communication is provided by obtaining a resistant communication relay which depends on APF based positioning algorithm. As shown in the Fig. 4, basically two limitations had been described, the first one communication range is outer band and the second one is collision avoidance band of the UAVs. These limitation bands are not provides a mechanism against the other obstacles except

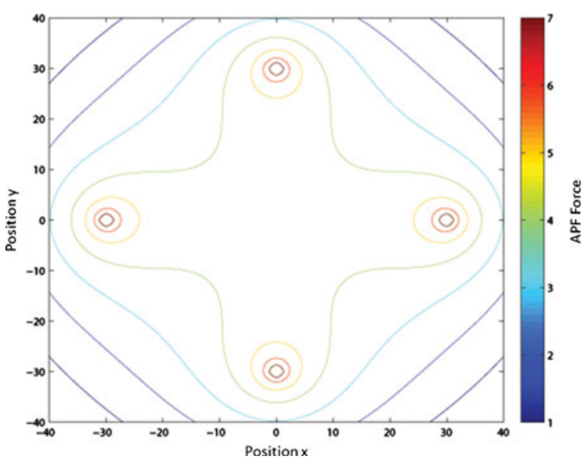

Fig. 3 Local minimum test with harmonic potential functions in APF

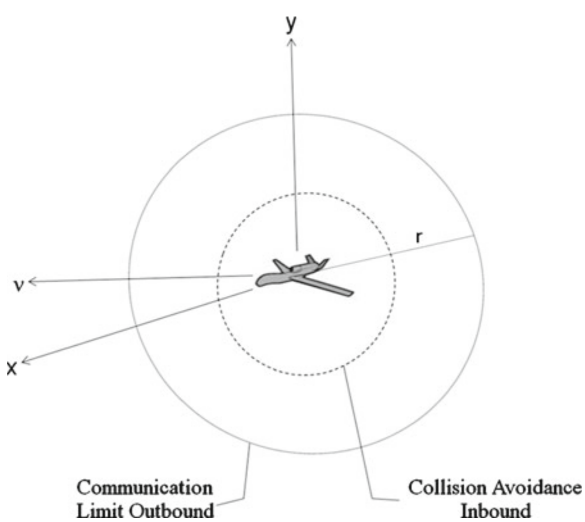

Fig. 4 Collision avoidance and communication range limit boundaries of UAVs

the other vehicles in formation. While formation established at higher altitude levels basically assuming that there is no obstacle and it has some advantages to provide an algorithm easily without collision risks with geographical obstacles. Furthermore flying at higher altitudes brings the long communication range and long endurance for formation. Except the High Altitude and Long Endurance (HALE) class platforms, especially for Medium Altitude and Long Endurance (MALE) and below class UAVs, this is unlikely to fulfill all the requirements due to their limited ceiling altitude. Their operation altitudes probably may contain geographical or other physical obstacles like buildings etc. while performing mission flight. So collision and obstacle avoidance mechanism must be provided autonomously to ensure safety during cooperative mission flight.

As shown in Fig. 5, attractive forces are on the outbound to keep the UAV in the communication range of the other UAV. Repulsive force is applied from the center point of the UAV communication range and provides collision avoidance by forcing other vehicle(s) to the communication range bound. In this work, each UAV has the same APF definition. Desired positions of vehicles can be detected by using identical APF algorithm for each UAV.

To provide collision avoidance between the vehicles which are the members of the communication chain, the APF model which is shown in Fig. 5 is enough. But it needs modifications especially to add obstacle avoidance futures to the chain members. Obstacles cause a risk to collision; furthermore they affect the positions of the UAVs in chain to provide effective wireless communication which is affected from obstacles. So, all of the APF models, positioning algorithms and communication performance tests must be redesign and implement to provide obstacle avoidance option to the group.

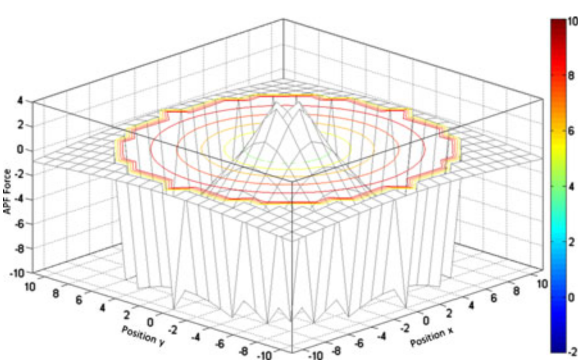

Fig. 5 Collision avoidance and communication range limit APF representation

4 Obstacle Model and Line of Sight Communication Based Positioning

In order to define obstacle avoidance supported APF based positioning algorithm, obstacle models in APF must be designed. As described in previous sections, obstacles are hill points in circular or elliptic shapes as repulsive forces which are defined as harmonic functions in APF. For only one obstacle in area, vector field of the repulsive forces can be seen in Fig. 6.

In order to prevent from local minimum conditions, the definitions of the obstacles are constructed by using harmonic functions in APF. For the simulation work which will be described in following sections, there are three major obstacles in the flight area and all of them are assumed to be higher than determined flight altitude of the UAVs.

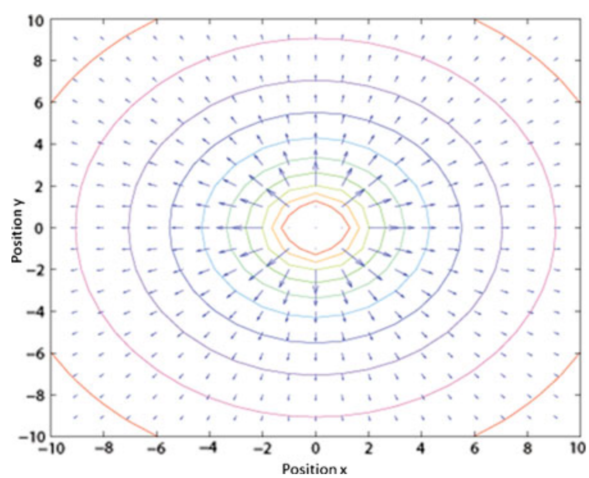

Fig. 6 Vector field representation of an obstacle in 2D APF

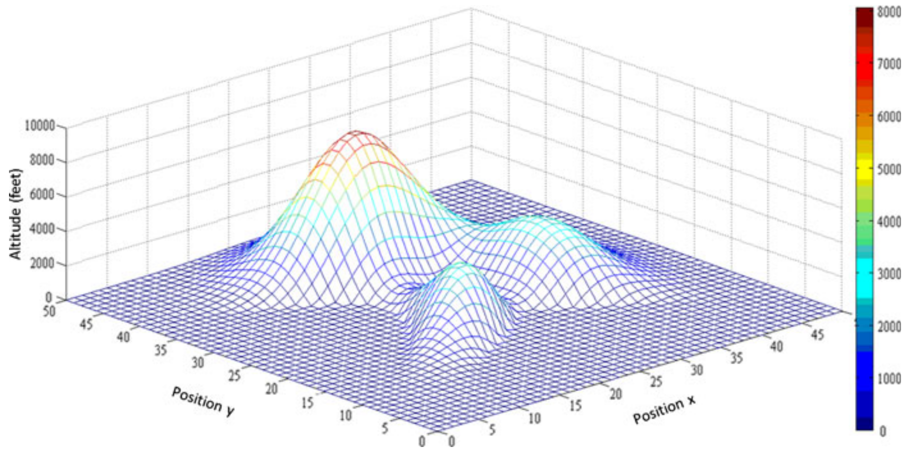

Fig. 7 3D representation of three geographical obstacles in flight area

Figure 7 shows the geographic obstacles taken as model scenario and highest point in the flight area is 8000 meters. In planning of the APF model, described obstacle borders which are shown in Fig. 1 must be defined as repulsive forces.

Obstacles are represented as elliptical shapes in APF. To model an obstacle, there are four main parameters;

- Center point of the elliptic shape,
- Ratio of two axes,
- Angle between y axis of the obstacle and the area,
- Force factor of the shape.

First three parameters are related to the shape of the obstacle and the last one is related with the repulsive force power. If the obstacle's elevation suddenly appears like a barrier or it is larger relatively to the others in 2d dimensions, the force factor coefficient will be higher.

By using the harmonic functions which are defined in formula 2, APF forces of the obstacles are obtained as shown in Fig. 8. As seen from the Figs. 8 and 9, there is no local minimum and every altitude level has different APF repulsive force as minus representation, "0" means maximum repulsive force in Fig. 8. Obstacle avoidance is important task in flight area. But, another important factor is establishing uninterrupted communication service between UAVs in formation. Although there are some successful applications on communication in rough and non-clear environment [18], in most of current well known wireless transmission technologies, an obstacle-free space between two communicating antennas are required to establish a clear and effective thus reliable communication. In this paper, presence of this obstacle-free space is called LOS.

As all the UAVs participating in the relay chain are assumed to be leveled at a specific altitude, 2D coordinates of the obstacles at the specified level are required to detect LOS on two dimension space (2D) between two UAVs. This has been accomplished by calculating contour points of given three dimensional terrain data (height map) at the specified elevation. LOS detection is done by using every two consecutive contour points as a line and checking intersection between

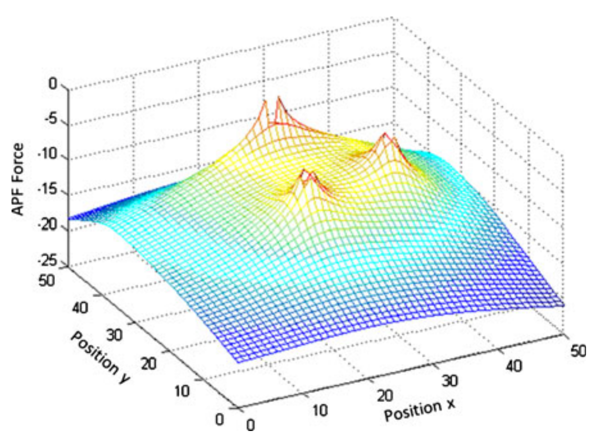

Fig. 8 Repulsive APF forces of obstacles in flight area

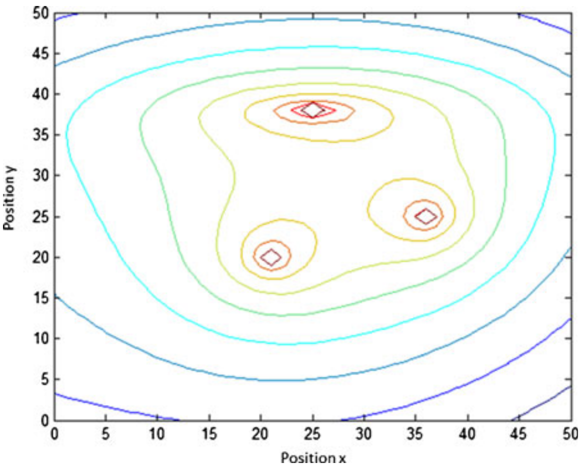

Fig. 9 APF forces gradients for the obstacles in 2D diagram

each of these lines and the line formed by two UAVs that are subject to communicate. Presence of intersection between any one of them leads to the absence of LOS between two UAVs and vice versa.

As the primary condition of a UAV relay chain, each UAV must always have at least two other UAVs in communication range. The only exceptions are; a) for the leading UAV which has to keep at least one UAV in communication range and move towards target and keep it in payload range, b) for the trailing UAV which has to keep base and at least one UAV in range. Also, to ensure the persistence of communication, each condition must be checked for each calculated coordinate they would navigate to.

As a result of LOS requirement for a reliable communication, obstacle avoidance is mandatory for calculation of next coordinate intended to move on. Because of that, each calculated coordinate is checked against having LOS with at least two UAVs. If two UAVs are found to be in LOS at the intended coordinate, then no more calculation is done to reduce processing cost thus simulation time of proposed approach.

Different positions of UAVs and different possible solutions which are determined by APF model with the awareness of obstacles and base positions are shown for communication chain establishment between target and base positions in Fig. 10. Bold lines represent the flight altitude of formation. Inner loops represent higher altitudes. The lines which are outside the bold one represent the LOS communication between vehicles. Squares represent the base position and the target point. APF and LOS check models must work

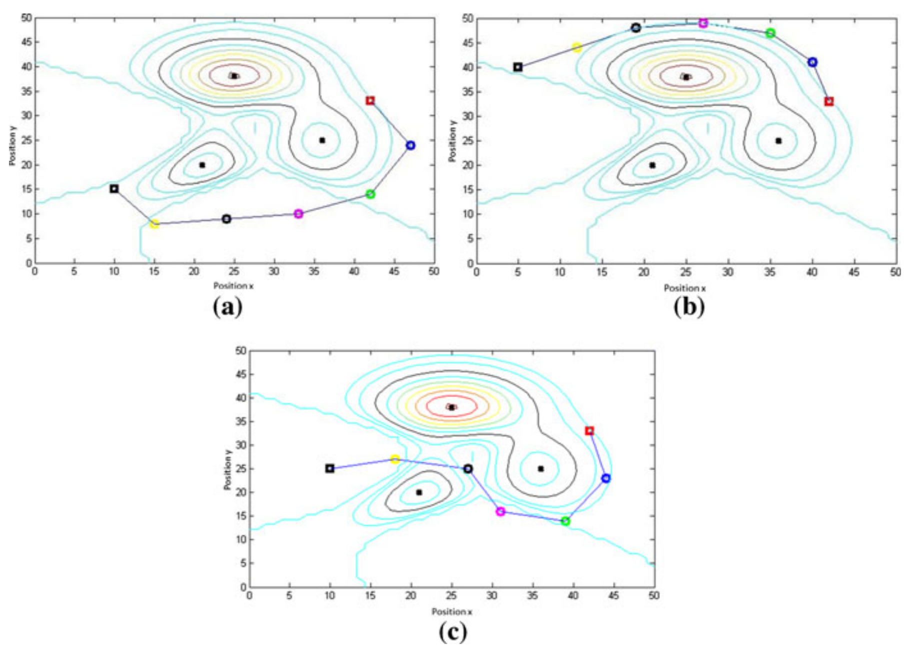

Fig. 10 LOS control between UAVs and stations for different sceneries. **a** Scenery-1 **b** Scenery-2 **c** Scenery-3

together as a single coherent system for collision avoidance and provides uninterrupted communication channels. Autonomous Obstacle Avoidance Communication Chain Model continuously calculates the appropriate UAV positions periodically in very short intervals. The task is similar to close loop control system after detection of each parameter like optimal flight altitude, obstacle forms, obstacle representation parameters, communication range, and initial positions of the UAVs and coordinates of base and target points. In order to maintain effective collision avoidance, Close Loop Control intervals must be very small and adaptively change based on UAV's speed. Figure 11 illustrates the logical design flow that is mentioned above.

By considering the UAV's capabilities like service ceiling altitude and uninterrupted communication range, optimum flight altitude between the geographical obstacles can be detected by using height map of the area. After deciding the optimum mission altitude, obstacle positions at this altitude can be derived from the height map and obstacle models -as two dimensional lines series- can be produced. APF parameters must be calculated to cover the shape of each geographical obstacle. Finally, positions of the UAVs must be calculated iteratively at every time interval during the mission.

In Fig. 11, P1 represents the current position of a UAV. P2is the resulting position which is calculated by APF to provide obstacle avoidance task and it represents the next position of the UAV after a Δt time period by using simple point mass model. Vn is the UAV which is subject to be communicating with the UAV under consideration. In order to keep the communication, P2 must be checked against presence of LOS. In case, LOS contact with at least two other UAV can't be established, P2 must be modified and re-checked. After the iteration results in P2' where required LOS contact is validated, vehicle moves to P2'

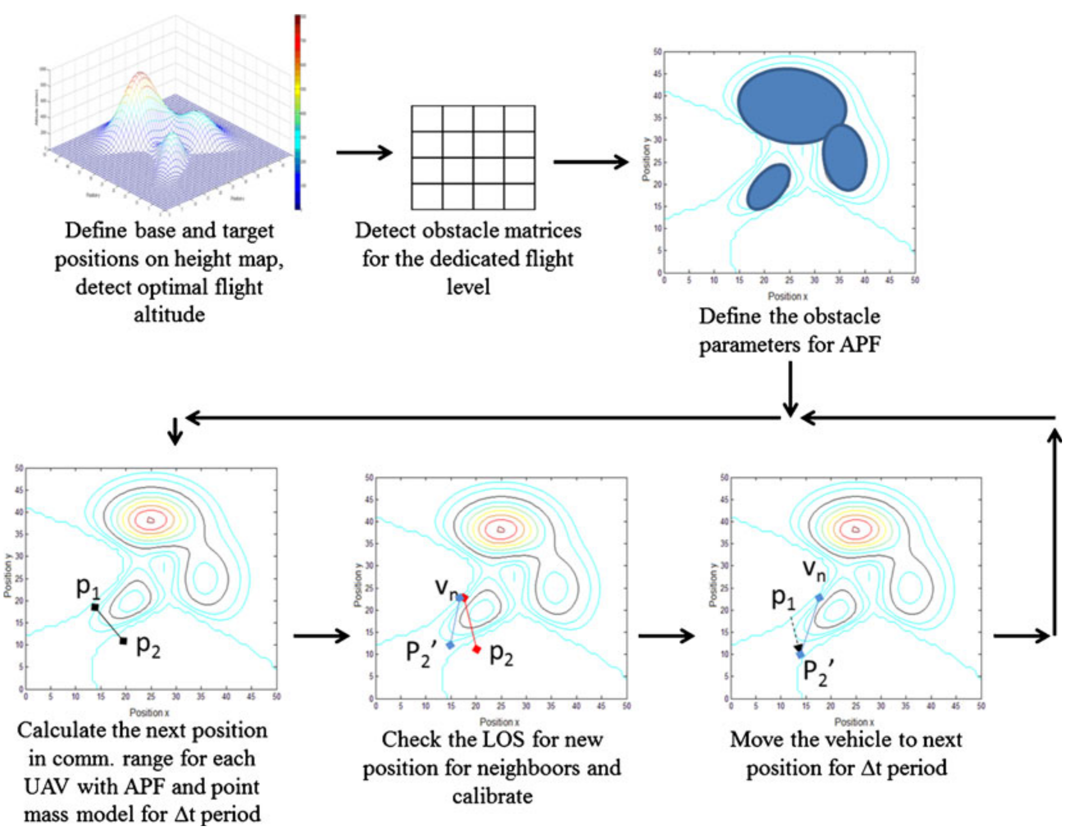

Fig. 11 Flow diagram for autonomous obstacle avoidance communication chain model

Table 1 Definition of the initial points of simulation in Matlab

Item	Initial position in 2d coordinate system	
	X	*Y*
Target	42	33
Head UAV	7	8
Bond UAV 2	6	6
Bond UAV 3	6	5
Bond UAV 4	4	4
Tail UAV	2	3
Obstacle 1	21	20
Obstacle 2	36	25
Obstacle 3	25	38
Base	10	15

position. This process calculates next positions of each UAV in the formation and loops during the mission flight.

UAV's positions must be defined by considering the LOS conditions with their neighbors. To provide LOS conditions, an algorithm is designed to improve the capabilities of APF based collision avoidance system. First of all, a target position for each UAV is determined by considering obstacle positions with APF. As a secondary process, these determined positions are checked for providing LOS conditions. If one of the positions does not provide LOS statements because of an obstacle between vehicles, determined target position of that vehicle is modified while providing the range and direction of the vehicle to target. This method is a kind of search approach and it works like shifting. For example, if current target point is not providing LOS and the vehicle is south-east point, target point is added with 1 in the x direction and checked again. If new target point is in the range and providing LOS while avoiding obstacles, this point selected as new target. If it is not suitable, one increment is applied in y direction and checked again. This loop continues until to find suitable target location. If suitable location is not found in the range limit, 1 value is subtracted in the x firstly and the y axis in orderly.

5 Simulations

By using the harmonic functions, APF models are generated and the obstacles are defined as elliptic repulsive force sources. The obstacle model which is defined in previous sections was used for modeling repulsive forces in the APF. Initial positions of the UAVs and coordinates of the target, base and obstacles points can be seen from Table 1. All of the positions are represented as X and Y coordinates in 2d coordinate system for 50 × 50 size area.

The potential field vector forces for each point in the defined area can be seen in Fig. 12 as a snapshot while simulation is running for the vehicle 3. Vectors are dynamically changing because of the other vehicles are mobile obstacles for the vehicle 3. Other vehicles and all of the obstacles are repulsive sources for each UAV. Target position is an attractive force for only Head UAV. Other UAV tries to reach correct position while

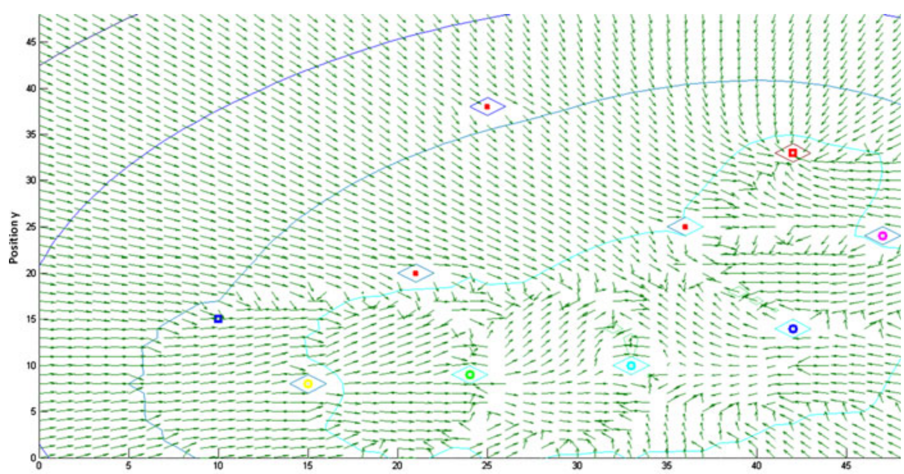

Fig. 12 Snapshot of the APF model vector forces for the bond UAV 3 during the simulation

providing LOS with their neighbors to keep alive communication channel during the mission.

The point mass model [7] is used for demonstrating the vehicle moves in vector field. The vector direction and intensity which are defined for the current point in the APF determines the movement of the vehicle. By using vector forces and point mass model, vehicle moves for a very short time period. By using this method, vehicle moves iteratively in the field and every movement of each vehicle affects the vector forces of the points which holds the other UAVs.

In order to evaluate the continuity of communication between leading UAV and the base, NS-2 simulation environment is constructed. Wireless node positions are gathered from the Matlab simulation. Required network simulation parameters are shown in Table 2. In difference from Matlab simulation, in NS-2, base and target points are also defined as wireless nodes to be able to effectively simulate leading UAV's payload range and line of sight existence to target, thus, real end-to-end communication. By its design, NS-2 simulator version (v2.34) used for simulations does not have any sort of module or component to enable definition of obstacles in simulation environment [19].

Due to the need of a realistic and solid validation of communication, NS-2 v2.34 source code is modified and re-compiled as to be able to support obstacle definition and calculate reception power based on LOS presence. TwoRayGround is selected as the propagation model of mobile nodes. Because of that, source code related to this propagation model in NS-2 is modified as;

- Obstacle data exported to NS-2 as an array of coordinates sorted to form a closed irregular shape,
- Functions in which reception power is calculated are modified to check intersection between two lines, one is formed by coordinates of sender and receiver UAVs, the other is iterate through subsequent pairs of obstacle data points.

In case of the intersection, the reception power is zeroed meaning no reception thus unsuccessful transmission. Constant Bit Rate (CBR) traffic model is used to simulate media streaming as one of the most possible UAV missions. Also, various data packet sizes (1024…64 bytes) together with various transmission intervals (120…4 ms.) are used to simulate different data flow rates. Results of numerous simulation with the given traffic setup have shown that, data flow from heading UAV towards base station never breaks, proving that LOSs between neighboring UAVs are continuous along mission flight.

The success of the approach has been validated and demonstrated within NS2 simulation environment as shown in Fig. 13.

Table 2 Wireless node and network environment parameters

Component	Setting	Note
Channel	Channel/wireless channel	All nodes are communicating over wireless channel
Propagation	Propagation/TwoRayGround	RXThreshold_ is set to obtain desired communication range
Network interface	Phy/WirelessPhy	All nodes have a wireless network interface
MAC	Mac/802_11	Enables most commonly used MAC layer protocol for wireless interfaces
Link layer	LL	Default Link Layer agent of NS-2 wireless node
LL queue	Queue/DropTail/PriQueue	FIFO - priority queue
Antenna	Antenna/OmniAntenna	Enables circular reception and propagation
Routing agent	AODV	Adaptive On Demand Vector Routing

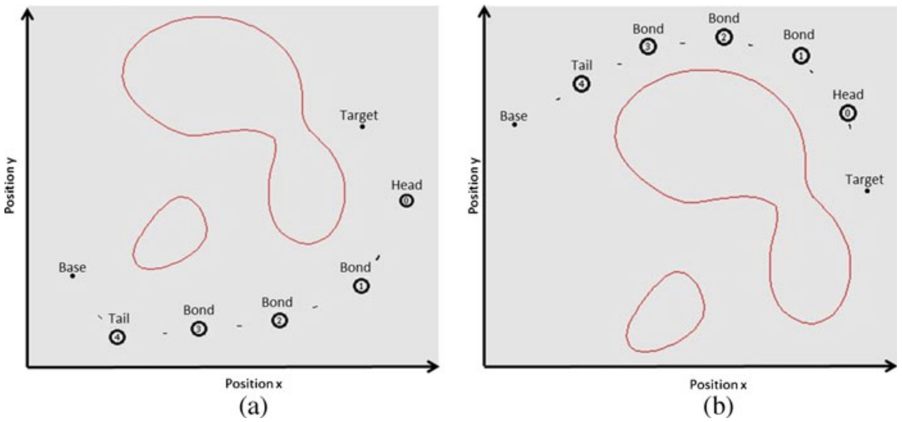

Fig. 13 Flow diagram for autonomous obstacle avoidance comm. Chain model in NS-2 for different sceneries. **a** Scenery-1 **b** Scenery-2

6 Conclusions

In this work, an obstacle aware airborne communication relay approach has been designed and implemented by using harmonic functions based on artificial potential fields for the autonomous UAVs. Basically, a solution for the calculation problem of autonomous UAVs position in a formation with obstacle and UAV collision avoidance has been proposed. The success of this novel approach has been demonstrated by MATLAB and NS-2 simulations. Dynamically changing APF model has been designed and simulated successfully to provide collision avoidance. LOSanother important factor for communication whichaffects the positions of the UAVs is implemented in APFdesign. The major concept of the approach isdefining the exact obstacle model in the APF.Digital height map data have been used to detectthe obstacle borders at the flight level of theformation. Vectors obtained using digitalobstacle data are modeled with elliptic shapes andused as obstacles for the APF. This approach isnot sensitive enough for the situations thatobstacles are very close to each other and there isenough space to pass a UAV between them. But, itis enough to show the efficiency of dynamicAPF model and to demonstrate obstacle avoidanceand collision avoidance tasks. Design andsimulation implementation of panel based obstacle modelin APF is planned as future work. Using the“panel method” in construction of obstacle modelswith APF, enables more accurate representations. One of the novel approaches is the demonstration of LOS model with APF calculations. Positioning algorithm has been optimized by using LOS model in the APF and the wireless communication between UAVs becomes more stable which are not affected from the obstacles. In this work, a fix flight altitude has been chosen. This is not the most efficient way in real time applications. Changeable altitude levels during the flight for the group of UAVs with dynamic obstacle detection and reproducible obstacle matrices, remains as an ongoing future work.

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