UAV Formation Maintenance in Linear and Curvilinear Trajectories

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***Abstract*— One of the important issues in aerial vehicle cooperation is the ability for fleet of vehicle to fly in a formation. Such a formation fly will improve the performance of the vehicle in their mission from organization point of view (Safety coverage technique, submission assignment, etc) and resources point of view (fuel, energy, etc) that will maximize the mission success results. However, maintaining formation for unmanned autonomous vehicle is much sophisticated than having human control in each vehicle in the case of manned one.**

Some researches proposed approaches to control the task assignment procedure for vehicles in hierarchy architecture. Others developed algorithms to achieve a cooperative behavior between vehicles. However, none of these researches discuss the formation maintenance and control, although the need for it will be dramatically by increase of using UAV in different applications.

This paper proposes a technique for autonomous aerial vehicles to maintain their position within a specific formation in a linear and non linear trajectory. It proposes a new technique called Water Level where every vehicle in a formation has an offset from the leader trajectory. During the vehicle fly plan, it compares its current offset with the formation offset and changes its velocity & heading to maintain that.

To test the performance of the above technique, it has been implemented using a Matlab R14 (C++) and then integrated with MultiUAV 2.0 simulation software. The water level technique was able to adjust the vehicle position in different amount of time based on different given specification..

I. Introduction

Future generations of UAV's will be able to autonomously cooperate with either manned or other unmanned aerial vehicles to accomplish strongly coupled tasks.

These are all computationally intensive optimization problems that require good situational awareness to achieve coordinated and cooperative behaviors. Some researches have been done in this field [3] [4] that propose approaches to control the task assignment procedure for vehicles in hierarchy architecture. In addition, some algorithms have recently been developed to achieve a cooperative behavior between vehicles [6] and some test-beds have been developed to implement these algorithms in real environment [5].

One of the important issues in aerial vehicle cooperation is the ability for fleet of vehicle to fly in a formation. Such a formation fly will improve the performance of the vehicle in their mission from organization point of view (Safety coverage technique, submission assignment, etc) and resources point of view (fuel, energy, etc). However, maintaining formation for unmanned autonomous vehicle is much sophisticated than having human control in each vehicle in the case of manned one.

This paper is discussing "The Maintaining Position" issue for a vehicle in its group relative to the current group formation. It proposes a technique called Water Level. The technique used by every vehicle in the fleet. Every vehicle assigned an offset from the leader trajectory to maintain during its flying plan. Then it changes its velocity and heading relatively based on the water level configuration variables.

To be able to implement and test the technique, I proposed an expert algorithm that will role as a formation control module and will manage the changing from one formation to another within a fleet of aerial vehicles. The expert algorithm will depend on some variables related to the vehicles in the fleet, and will generate an intermediate hypotheses that will depend on it in taking the final decision.

I used C++ under Matlab r14 environment to implement both water level technique and the expert algorithm. Then I integrated them with MultiUAV 2.0 simulation software [1] to simulate the action and evaluate the results.

II. METHODOLOGY

For a group of autonomous aerial vehicles that should fly in a formation, every vehicle has a unique id (Vehicle ID) and formation position number (Vehicle PN) that determine its position in the formation. The vehicles are flying in 3D environment and using passive ranging Global positioning system (GPS) to determine their positions in the globe. In this paper we will use the two dimension values, Longitude(X) and Attitude(Y) in the maintaining position technique and changing formation algorithm. However, every vehicle will have a fixed Longitude (Z) value based on the formation position assigned to it.

Every group has a communication system that allows their members to exchange messages and information during the flying. An authorization and security system is used in association with the communication system to force the role of receiving and broadcasting information. For example, the leader of the fleet is the only vehicle allowed to issue orders to switch from a formation to another and it gives the command in orders for the rest of vehicles.

A formation structure should be initialized and assigned to the group at the beginning of flight. Choosing a formation for a group depends on two values; Number of vehicles in the group and the formation pattern. For example, the formation of three vehicles could have left wing pattern or right wing pattern as shown in Fig 1

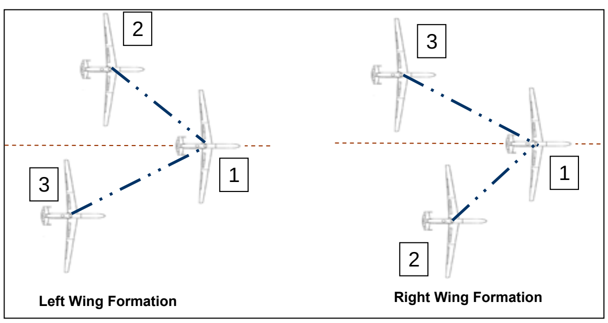

Fig. 1 Formation Selection.

III. FORMATION STRUCTURE

The formation constructed by assigning every vehicle in the group a position in the formation. This assignment is done by mapping (Vehicle ID) with (Vehicle PN). The leader of the groups always take position number one (Vehicle PN = 1).

Every position in a formation specified by assigning offset values relative to the formation leader (Position 1).

The offset values are: (See Fig 2)

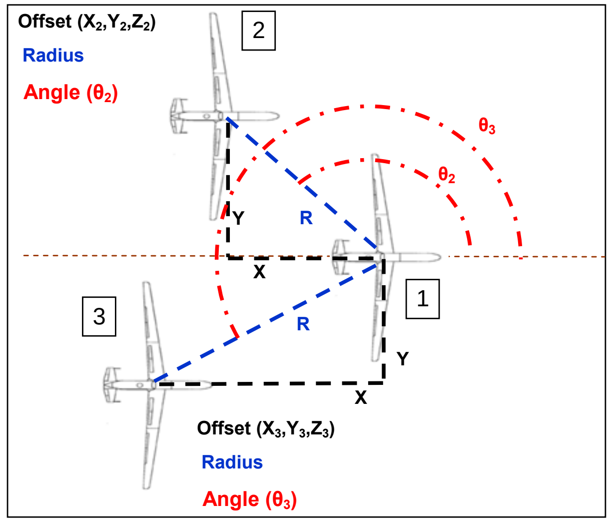

Fig. 2 Formation Structure.

1) Offset X: an X axis offset value from position number1.It is measure in coordinate unit.
2) Offset Y: a Y axis offset value from position number1.It is measure in coordinate unit.
3) Offset Z: a Z axis offset value from position number1. It is measure in coordinate unit.
4) Distance R: is the distance from the leader and calculated using the offsets X, Y.
5) Angle θ: is the un-clock wise angle of the vehicle at that position that make it with the vehicle at position 1. It is calculated using the Distance and X, and Y offsets.

Angle θ is calculating using the following formula:
SlopeAngle = atan((Y1 – Y0) / (X1 – X0))
sumA = SlopeAngle +180
Angleθ = sumA - (fix(sumA/180)*180); For Y1>= Y0
= sumA - (fix(sumA/180)*180) + 180; For Y1 < Y0
Where fix: is the round function toward zero

The reason for using Angle θ is the need to have a relative value for a vehicle to use in its position evaluation relative to the leader (Position 1) at any time during the flight. Although "Distance" is a relative value, by only using it you can't determine the position of the vehicle in the globe. It could be any point on a circle surround with R=Distance, taking in consideration the X and Y axis.

IV. FORMATION TRAJECTORY

The trajectory of every vehicle is specified by set of waypoint loaded to the vehicle memory. Those waypoints calculated based on every vehicle position in the selected formation. So by following that waypoint, every vehicle will fly in its track related to its formation.

To calculate the waypoints, first the trajectory of the leader specified based on the flying plan. Then initial waypoint for every vehicle is determined. They could be different initial waypoints or one same initial waypoint if we assume that the vehicles will take off from same runway. After that, the coordinates of the rest waypoints are generated using:

1. Transition Operation: for every vehicle, to generate a new waypoint (Xi,Yi,Zi) in the same direction, a (x',y',z') transition applied on the previous waypoint (Xi-1,Yi-1,Zi-1).

2. Rotation Operation: for every vehicle, to generate a new point (Xi,Yi,Zi) in different direction, a θ' angle rotation is applied on previous (Xi-1,Yi-1,Zi-1) using one fixed (x',y',z') center.

V. Position Maintaining (Water Level Technique)

Although the waypoints trajectory generated based on the assigned formation will keep the vehicle in its track relative to the leader vehicle, the vehicle distance from the leader on the track still needs to be maintained using different variables.

During the flying, the leader vehicle broadcast the following leader data to the rest of vehicles in the fleet:

1. Coordinates (X,Y,Z)
2. Heading Angle
3. Velocity

Based on these information, every vehicle in the groups calculates the position coordinates difference (x,y,z), the distance (r) , and the angle (θ) relative to the leader. Then it compares them with its formation position values. Based on that comparison, the vehicle changes its velocity (Increase/Fix/Decrease) using position maintains technique called Water Level as shown in Fig 3.

Water level technique uses threshold limits (S) to classify the difference between current vehicle angle and its formation position (D) into three areas:

1) Increasing/ Decreasing area (D <= -S) or (D >= +S): the vehicle velocity increased or decreased using the following formula:

Vehicle Velocity = Old Velocity + (Angle Differences/Formation Angle) * Old Velocity

If Vehicle Velocity > Upper Limit : Velocity = Upper Limit.
If Vehicle Velocity < Lower Limit: Velocity = Lower Limit.

2) Stabling area (-S<D<-S/4) or (S/4<D<S): in this area, the velocity is not updated and continues with the same value that the vehicle has at the time enters this area.

3) Fixing area (-S/4<= D =<S/4): when the difference arrives to that range, the vehicle velocity takes the velocity of the leader at that time.

In the increasing decreasing area, the velocity is updated every period of time called "Velocity Update Gab" that reset every time an update held. The reason for this gab is to give the new velocity the minimum range needed for its effect to take role.

In some cases, when the vehicle becomes closer to the required position, its velocity is little bit more than the leader. So it passes the required position then it decreases the velocity until it enters the fixing area. That is why this technique called water level.

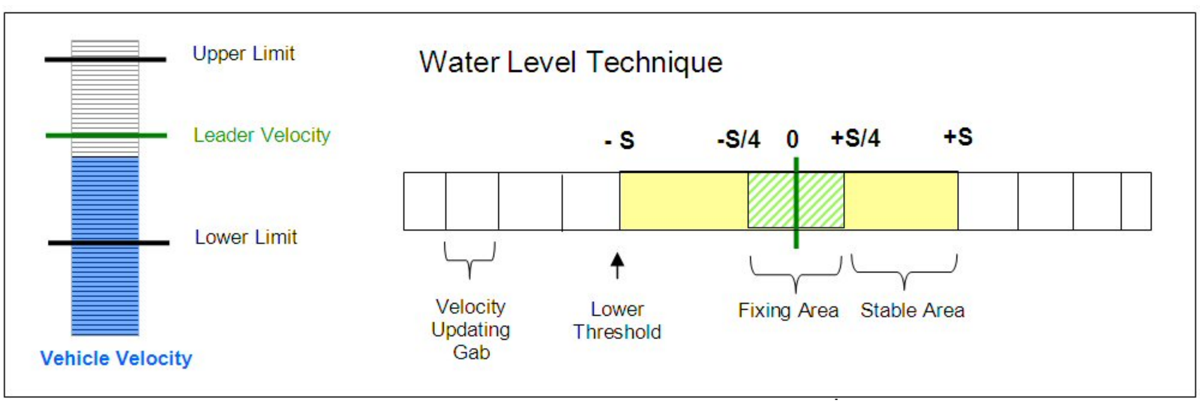

Fig. 3 Maintaining Position Technique (Water Level).

VI. Maintaining Position Test Cases

We will measure our result by evaluating the time required for group of vehicles that start flying in one vertical column formation to form the assigned formation.

For same number of vehicles that assigned a specific formation, the time varies based on the water level (WT) variable that we set.

If we use the following WT variables to form a 3 vehicle right wing formation:

- *Velocity upper limit = 500*
- *Velocity lower limit = 50*
- *Upper threshold (S) = 10*
- *Lower threshold (S) = -10*
- *Fixing Area (-S/4,S/4) = [-2.5,2.5]*
- *Velocity Updating Gap = 25*

The vehicles will form the left wing formation in 33.4 Seconds as shown in Fig 4 below.

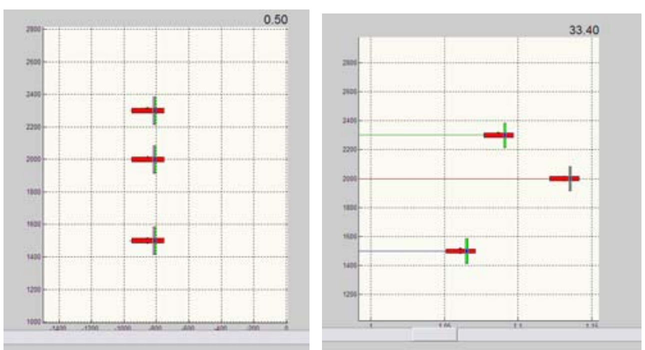

Fig. 4 Forming a left wing formation.

VII. Conclusion

To increase the performance and the efficiency of the water level technique, the configuration variables should be selected carefully. However, for a different environment there should be different variables suitable for it.

I convert the expert module to C language and place it above my other functions in the Formation Control Software. Then I integrate it with the test bed software associated with other modules that I develop to manage Multi Autonomous Aerial Vehicle formation control.

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