Deconfliction of Multiple, Autonomous Vehicles

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Abstract

The UCAV research community envisions the use of multiple unmanned aircraft that perform coordinated strike and reconnaissance missions with manned aircraft. However, there is a missing technology that must be developed before unmanned systems realize their full potential – self-organizing separation assurance.

According to Dr. Birckelbaw, program manager for the DARPA UCAV program, “That's the most stressful case we're finding - proving to the warfighter that UCAVs will be able to reliably defend [manned aircraft while staying] deconflicted with the rest of the strike package” [1]. Pilots want assurance that UCAVs will stay a safe distance from manned aircraft.

Even with airborne separation assurance systems, the challenge of controlling and coordinating large numbers of unmanned vehicles seems daunting. USAF Gen. Mike Loh (Ret.) said of this problem, “Once you get more than two or three [unmanned aircraft] in the air at a time, you have complexity you can't imagine” [1]. Operational planners need to know there will be a way to control and coordinate a large number of autonomous vehicles.

This paper discusses a paradigm for coordination and control of multiple autonomous aerial vehicles. The proposed paradigm, which is based on potential field algorithms, has proven extremely robust during simulation and testing.

Conflict Detection and Resolution

Control of multiple autonomous vehicles, and operation of those vehicles in mixed airspace, will require technology development in separation assurance algorithms. These algorithms will assure conflict-free trajectory planning, as well as provide basic autonomous navigation capabilities. Rockwell has previously demonstrated the use of potential field algorithms for this purpose [2].

Over the last few years, Rockwell has been developing conflict detection and resolution (CD&R) technologies for separation assurance in the future air traffic management concept known as "free flight" [3]. We have developed the foundations for a highly robust, distributed algorithm that maintains positive separation between aircraft in a given vicinity. The approach we are using, based on potential field algorithms, functions without the need for a dedicated, centralized command and control infrastructure. This feature makes the algorithms especially attractive to UAV and UCAV operations.

A conflict is defined as a "predicted violation of a separation assurance standard" [4]. Under this definition, a conflict exists when two aircraft will come within a certain distance of each other at some time in the future. Obviously, the existence of a conflict depends on the type and parameters of the chosen prediction algorithm.

Conflict detection (CD), therefore, is the prediction of a future violation of a separation assurance standard [5]. For the civil aviation application, the separation assurance standard is defined by an airspace regulatory agency (e.g., FAA). For civil aviation, an example of the separation standard is five miles lateral spacing and 1000 feet vertical spacing for enroute cruise. Transoceanic spacing is specified in terms of minutes in-trail. Obviously, for military operations, the minimum separation can be much lower.

Conflict resolution (CR) is the function that provides guidance cues or trajectory generation to avoid conflicts. The resolutions can be in the form of discrete instructions similar to current TCAS (Traffic Alert and Collision Avoidance System). Preferably, the conflict resolutions can be performed on a strategic time frame in the form of flight plan modifications. The modified flight plan is then loaded into the aircraft's flight management system.

Conflict detection and resolution functionality differs from TCAS in two ways. TCAS is a *collision avoidance system*. It is intended to prevent a collision of metal-to-metal when the primary means of separation assurance have failed. It is a "safety net." CD&R, on the other hand, is a *separation assurance system*. It is intended to be the primary means of separation assurance, not a safety net. Consequently, the look-ahead window of CD&R is farther than TCAS – minutes, rather than seconds. CD&R should be based on the intent (e.g., a flight plan) of the conflicting aircraft, rather than just the instantaneous velocity vectors. The resolution maneuvers for CD&R are intended to be more strategic in nature than TCAS Resolution Advisories.

Potential Field Algorithms

One approach to conflict detection and resolution is based on the intuitive physical principle of potential fields, which is illustrated in Figure 1. In that figure, several positively charged particles have been released into a space that contains fixed negative charges. The positive charges will tend to be drawn toward a fixed negative charge because of the mutual attraction of their opposite charges. At the same time, the positive particles tend to maintain distance between each other because of the mutual repulsion of their like charges. An analogy could be drawn to a free-floating positive charge as an aircraft and a fixed negative charge as its destination. This analogy provides a crude model for developing conflict resolution algorithms. Aircraft on intersecting courses are treated as charged particles that repel each other.

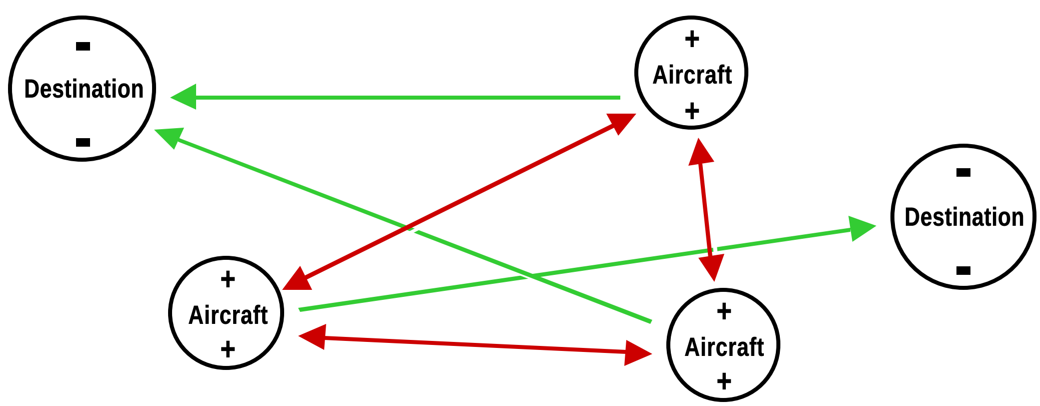

Figure 1. The Potential Field Metaphor

This simple, elegant approach has proven extremely robust in simulations that involve large numbers of aircraft in a confined airspace. For example, in Figure 2 and Figure 3 the results of two simulations are depicted. The results in Figure 2 are results from running a scenario without the separation assurance algorithm. The results in Figure 3 are the results from the same scenario, but with the use of the modified potential field algorithm to provide conflict-free trajectories. The vertical axes are the pairwise distances between the aircraft involved in the simulations. The distances have been scaled such that the desired separation is 1. The horizontal time axes have similar been scaled such that the average conflict time is 1. The normalization is intended to emphasize the range of possible applications, without the distraction of specific units that may be associated with a specific domain (e.g., transport category aircraft, long-range UAVs, UCAVs). As the maneuverability of the aircraft improves, the magnitude of the desired separation can be decreased. For these scenarios, there are eight aircraft, all originally converging to within a 0.6 unit radius. Therefore, the results in Figure 3 show that the algorithm was successful at achieving a desired separation for an extremely challenging conflict involving eight aircraft.

In addition to providing resolutions to extremely challenging conflicts, the algorithm has also been shown to gracefully degrade as communications reliability deteriorate and as aircraft maneuverability decreases [2].

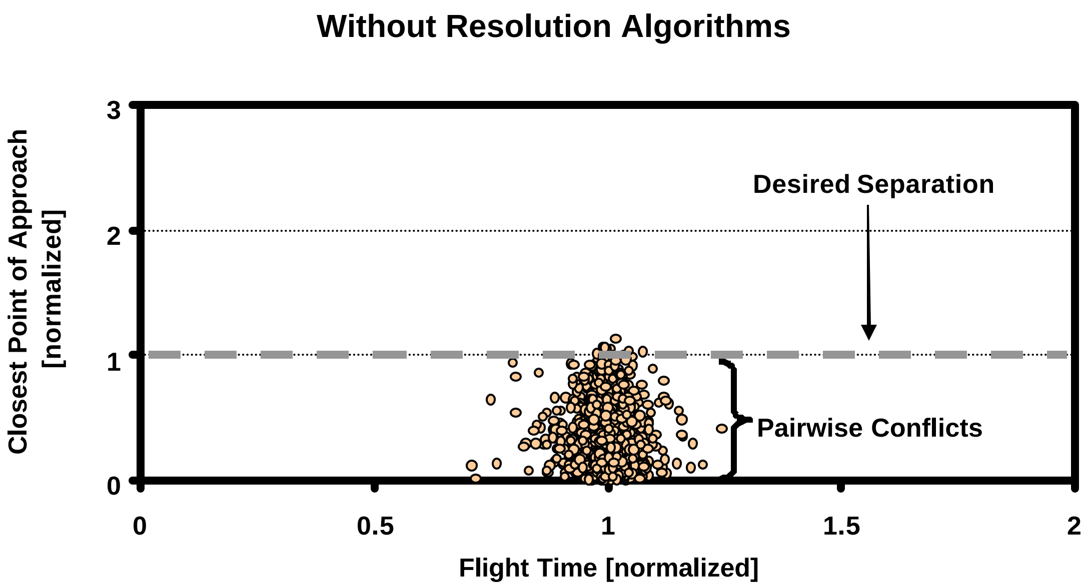

Figure 2. Eight Aircraft Scenario, ***Without*** Conflict Resolution

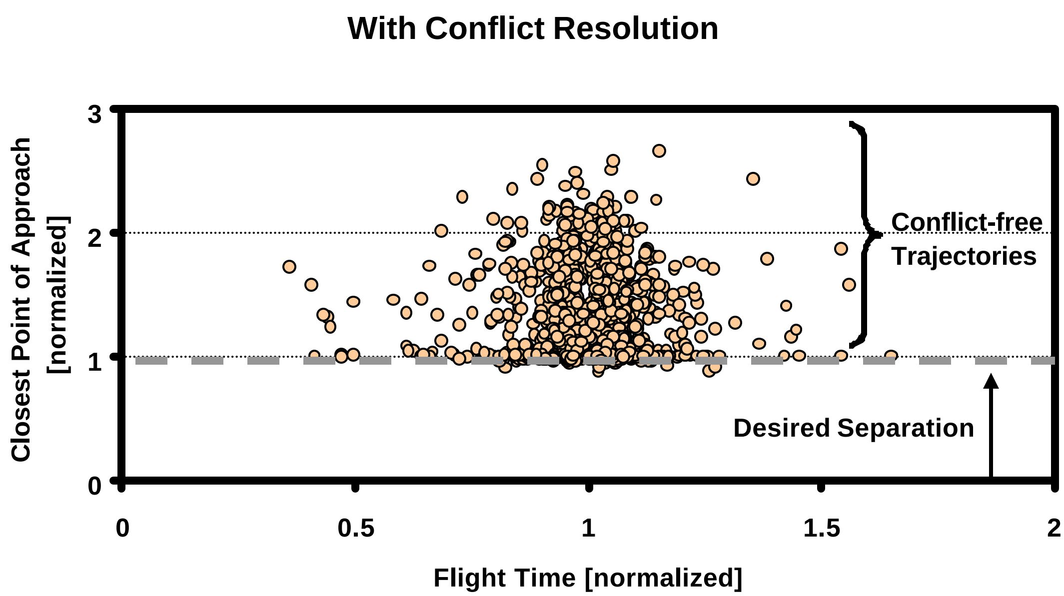

Figure 3. Eight Aircraft Scenario, ***With*** Conflict Resolution

Algorithm Characteristics

The potential field algorithm demonstrates several other useful characteristics, which are beneficial for use in unmanned systems.

- In the absence of traffic conflicts, the aircraft proceed directly to their destinations. Because of this feature, the algorithm can serve as the foundation of the vehicle's guidance scheme.

- The algorithm is applicable to multi-aircraft conflicts. The majority of conflict resolution research has focused on simple two or three vehicle conflicts [6]. Few researchers have performed tests on scenarios involving eight converging aircraft.

- The response to a given conflict is appropriate to the time proximity and magnitude of the conflict. That is, small conflicts far in the future result in very minor deviations in course and speed while larger and/or more immediate conflicts result in larger deviations.

- The guidance of each vehicle can be based on the assumption that the other vehicle will not maneuver to avoid a conflict. The application of this feature may be useful in a mixed (manned and unmanned) environment. In this case, the unmanned vehicles could be assigned the responsibility of maneuvering to avoid conflicts with their manned counterparts.

  This last feature is demonstrated with Figure 4 through Figure 7. In Figure 4, four converging aircraft all maneuver to avoid a four-way conflict. As can be seen, each aircraft maneuvers to their left. (A small perturbation is added to the scenario to break the “head-on” singularities.) The six pairwise distances between the four aircraft is plotted in Figure 5, which shows that the aircraft all maintained the desired separation.

Now, the question to be answered is this: “What if one of the aircraft does not adjust its trajectory in response to the conflict?” Figure 6 is a plot of the trajectories for the identical scenario using the identical algorithm. The difference is that one of the aircraft does not maneuver to avoid the four-way conflict. The aircraft flying from left to right continues on its original intended course. A comparison of Figure 4 and Figure 6 shows that the three maneuvering aircraft must make additional compensation for the lack of cooperation on the part of the fourth aircraft. However, Figure 7 shows that the desired separation is still achieved. In fact, the desired separation is achieved without a-priori information that the left-to-right aircraft was not going to maneuver.

- The proposed paradigm is also applicable to the problem of generating conflict-free guidance in the presence of obstacles. The obstacles may be hazardous weather, terrain, or enemy positions. The obstacles have a “charge” associated with them and the conflict free trajectories are generated based on the presence of that repelling field. Figure 8 shows an example of three aircraft simultaneously avoiding each other and two obstacles.

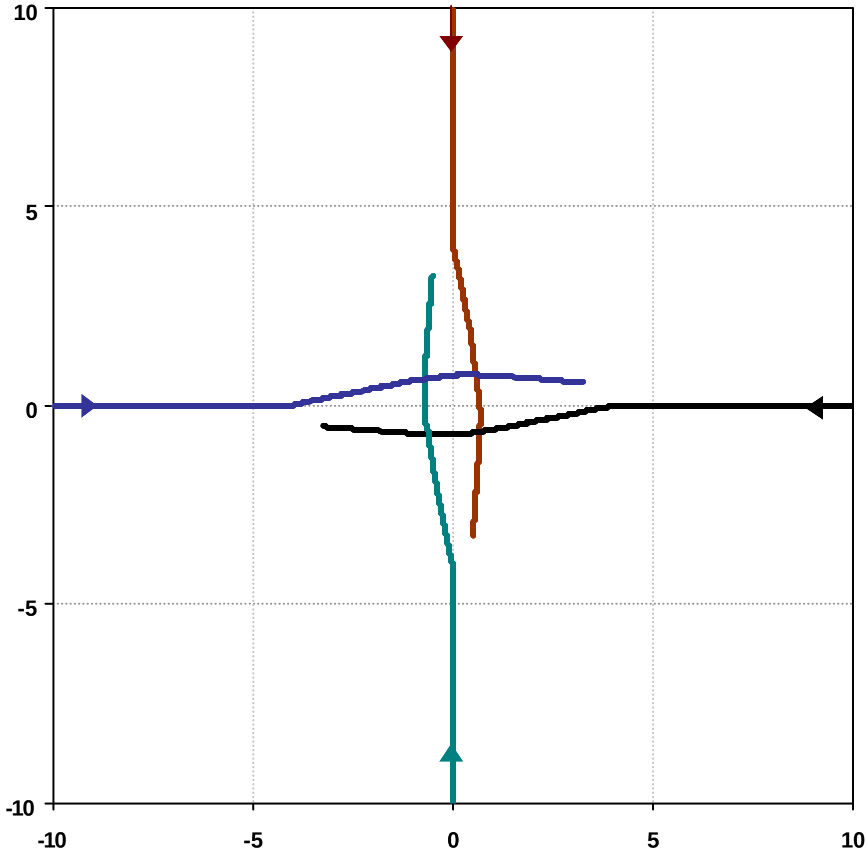

Figure 4. Four Aircraft Maneuver to Avoid a Four-way Conflict

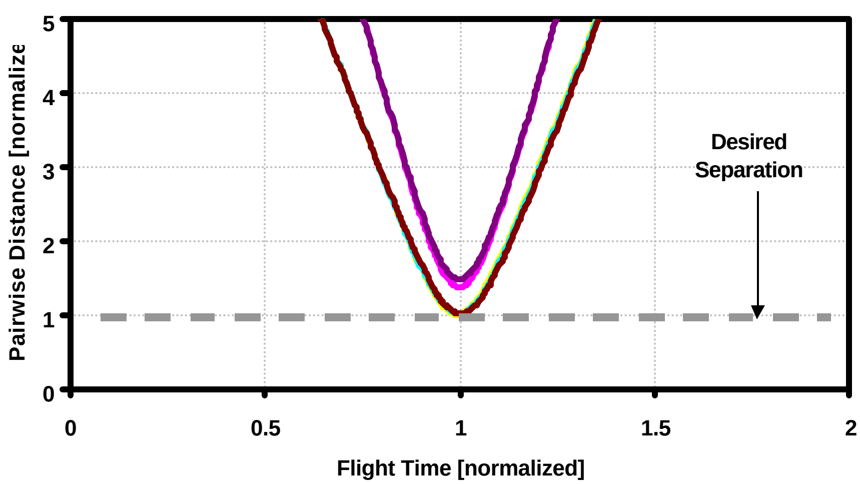

Figure 5. Pairwise Distances for Four Maneuvering Aircraft

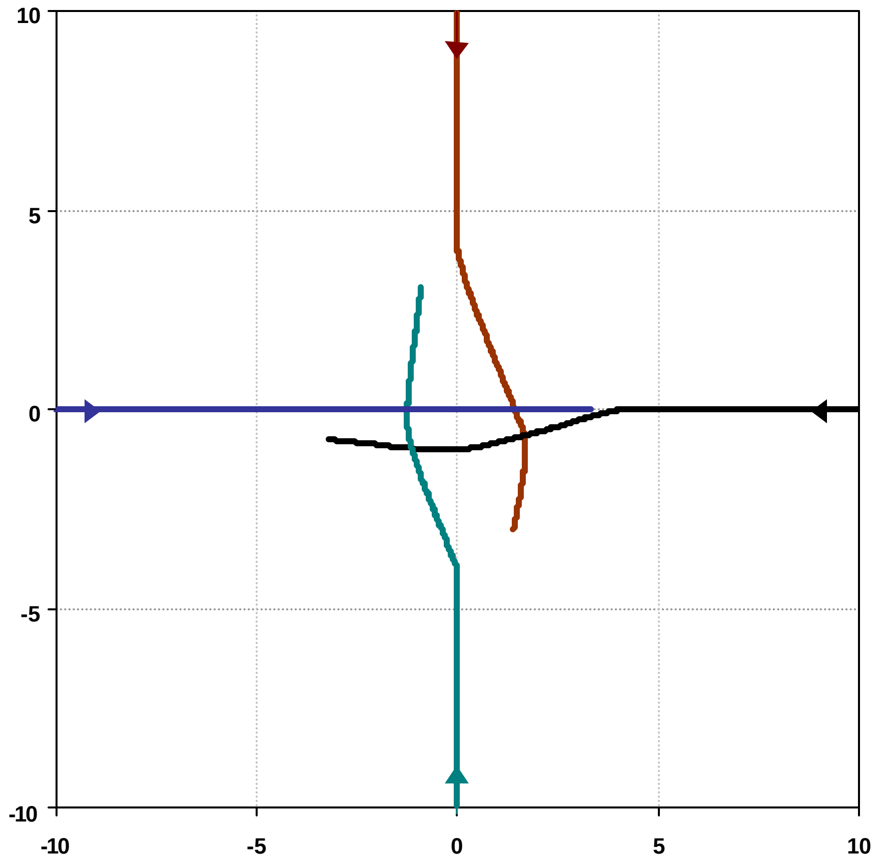

Figure 6. One Aircraft Does Not Maneuver to Avoid the Conflict

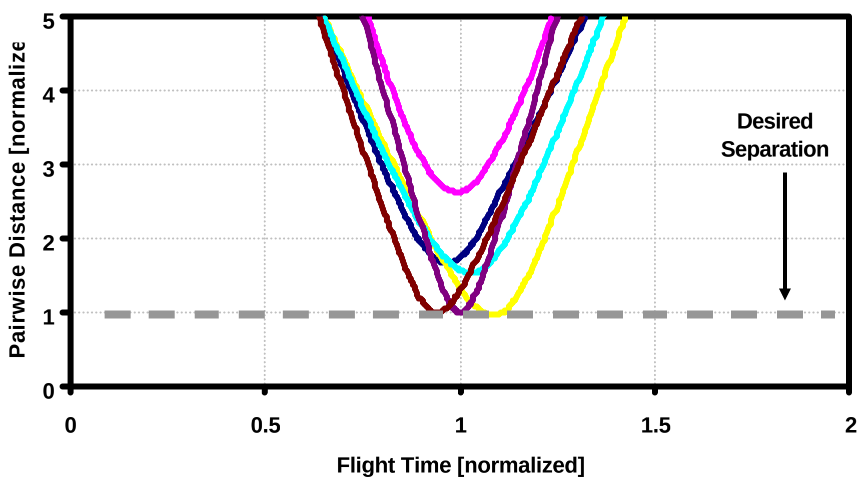

Figure 7. Pairwise Distances for Only Three Maneuvering Aircraft

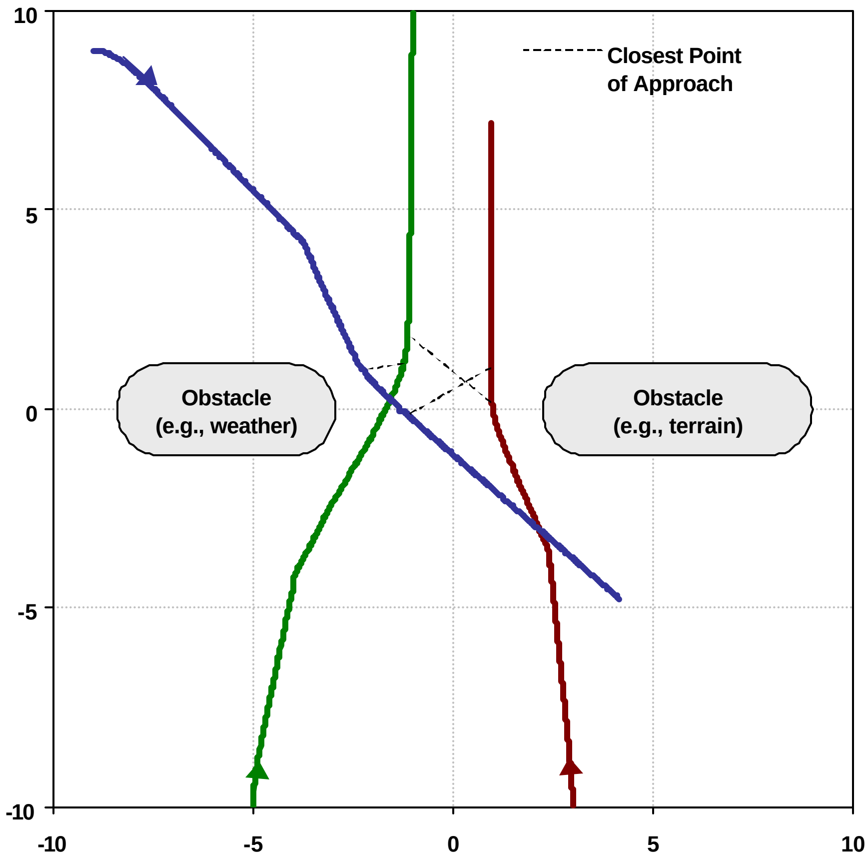

Figure 8. Three Aircraft and Two Obstacles

Conclusion

The results of an on-going study suggest that field potential algorithms may be a feasible basis for deconflicting the flight of multiple autonomous vehicles. Previous studies have shown the robustness of this approach under constraints in maneuverability and data link communications. This approach has been extensively tested for scenarios involving eight converging aircraft. The results in this paper confirmed that the algorithm performs well even when one of the aircraft does not maneuver to avoid the conflicts. Additionally, preliminary results were included of scenarios involving airspace obstacles.

The challenges that we are currently addressing include queuing, flight plan generation, single axis maneuvers, and required time of arrivals. The current algorithm does not handle the problem of queuing aircraft – into an airport or over a target, for example. Also, as can be observed from the trajectory plots, the flight paths are smooth, continuous curves. There are situations where a piece-wise linear flight path is preferred – for loading into a flight management system, for example. A third research area is single axis resolutions. Currently, changes to heading, speed, and altitude are simultaneously supported. When conflict resolutions are limited to maneuvers in only one of these variables, how does the algorithm behave? Finally, and perhaps most importantly, we would like to support conflict-free trajectories that include 4D waypoints – that is, required times of arrival.

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