Rendezvous of Multiple UAVs with Collision Avoidance using Consensus

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ABSTRACT
This article addresses the problem of multiple Unmanned Aerial Vehicle (UAV) rendezvous when the UAVs have to perform maneuvers to avoid collisions with other UAVs. The proposed solution consists of using velocity control and a wandering maneuver, if needed, of the UAVs based on a consensus among them on the estimated time of arrival at the point of rendezvous. This algorithm, with slight modification is shown to be useful in tracking stationary or slowly moving targets with a standoff distance. The proposed algorithm is simple and computationally efficient. The simulation results demonstrate the efficacy of the proposed approach.

Keywords: multiple UAV, rendezvous, collision avoidance, consensus

Quite often Unmanned Aerial Vehicles (UAVs), in multiple UAV missions, are required to come together, or rendezvous, to exchange information and resources. Thus, rendezvous is important in many coordination and cooperation tasks involving multiple UAVs. For example, in a target prosecution mission, the UAVs are required to form a coalition and prosecute the target simultaneously by rendezvousing at the target to inflict maximum damage (Manathara et al., 2011). This paper addresses multiple UAV rendezvous in the presence of collision avoidance, that is, the UAVs en route rendezvous will have to perform avoidance maneuvers to avoid collisions with other UAVs in the environment, and still achieve rendezvous. The collision avoidance maneuvers will take the UAVs out of their predetermined trajectories thus disrupting the scheduled rendezvous. The objective of the UAVs is to attain rendezvous at the predetermined point even in such situations by communicating with each other to iteratively reschedule the time of rendezvous.

1 Introduction

There have been contributions from the multi-agent and the multi-robot communities in devising algorithms for achieving rendezvous. In these works, multiple agents or multiple robots arrive simultaneously to a common location by cooperating via communication with each other (Lin et al., 2003; Notarstefano & Bullo, 2006; Tiwari et al., 2004; Das & Ghose, 2009). Rendezvous of the agents or robots occurs in these cases via positional consensus which is achieved through global or local communication. Therefore, the rendezvous usually does not occur at a predetermined point, but is a function of the initial positions
of the agents. A different approach is presented by Sinha and Ghose (2006) wherein a linear cyclic pursuit strategy is used by agents to attain rendezvous to a desired point by an appropriate choice of controller gains and switching of pursuit sequence. All the above papers do not consider the kinematic constraints of UAVs like turn rate limitations and velocity bounds. Linear cyclic pursuit can be extended to a non-linear cyclic pursuit by adding the non-holonomic constraint of minimum radius of turn, in which case, Sinha and Ghose (2007) show that the cyclic pursuit cannot achieve rendezvous at a point but rather will result in a ‘rendezvous about a point’ which is equivalent to the notion of ‘target tracking with a standoff distance’ in this paper. The problem of rendezvous has been earlier addressed in the UAV community. Furukawa et al. (2005) propose a strategy by which multiple UAVs arrive simultaneously at a target by using time optimal control of orientation and speed. McLain and Beard (2005) solve the optimization problem of minimizing time to rendezvous point of a group of realistic UAVs, as well as their times of exposure to known threats. Although these papers account for turn rate limitations and velocity bounds present in a realistic UAV, and avoidance of obstacles known a priori, they do not consider collision avoidance maneuvers that a UAV has to perform to avoid other UAVs en route. This paper proposes a solution to the problem of multiple UAV rendezvous under collision avoidance via a consensus algorithm implemented by the UAVs. It is assumed that the UAVs are capable of communicating with each other to attain a consensus on their Estimated Time of Arrivals (ETAs) at the predetermined rendezvous point. The individual UAVs use velocity control within bounds and a wandering maneuver, if necessary, to alter their ETAs to meet the rendezvous requirements. Also proposed is a slight modification of this algorithm which can be used to track stationary and slowly moving targets from a standoff distance.

2 Rendezvous via Velocity Control through Consensus on ETA

One way to achieve rendezvous of multiple UAVs is by the individual UAVs adjusting their trajectories to reach a predetermined location in space at a predetermined time. This is possible if the UAVs know a priori the positions of the obstacles en route, and do not have to perform maneuvers to avoid collisions with other UAVs that they encounter on the way. However, in the presence of collision avoidance maneuvers which cause UAVs to deviate from their nominal paths, it may no longer be possible, even if the UAV flies at its maximum speed, to arrive at the rendezvous location at the predetermined time. Therefore, in such cases, this paper proposes the iterative modification of the rendezvous time through communication between UAVs. This paper assumes a kinematic UAV model with a minimum radius of turn, and upper and lower velocity bound constraints. A UAV $U_i$, $i = \{1, \ldots, N\}$ has the following kinematics

\[
\begin{align*}
\dot{x}_i &= v_i \cos \psi_i \\
\dot{y}_i &= v_i \sin \psi_i \\
\dot{\psi}_i &= a_i
\end{align*}
\]

where, $v_i$ is its velocity, $a_i$ is its acceleration that belongs to $\{-v_i/a_i, 0, v_i/a_i\}$ (that is, UAVs can either turn left, go straight, or turn right with minimum turn radius $R_{\text{min}}$). The paper considers only tightest turns and straight line path maneuvers since time optimal rendezvous paths consist of these components
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only (Dubins, 1957). Further, the use of only three turn rates keeps the algorithm simple to implement. It is possible to envisage an algorithm that uses variable turn rates to achieve rendezvous. However, this would increase the computational complexity of the algorithm thus making it difficult to implement on small UAVs with low computational capabilities. Further studies are needed to develop a computationally efficient rendezvous algorithm that uses variable turn rates. This effort, while quite important, is beyond the scope of the present paper.

The time at which rendezvous occurs, in case of deviation of any UAV in the group from the predetermined path, is modified using a consensus protocol on the ETAs of the UAVs. To achieve a consensus on ETA at the rendezvous point, any consensus protocol can be used. For the purpose of demonstration, this paper uses the average consensus protocol. In an average consensus protocol, the new ETA agreed upon by all the UAVs is the average of the ETAs of all the UAVs. Also, a UAV need not communicate with all other UAVs, but only with its neighbors. In that case, if the communication graph is connected, then average consensus is guaranteed (Olfati-Saber et al., 2007). Thus, the proposed algorithm can be used even when the UAVs have only limited communication ranges but the communication graph is always connected. It is also assumed that there is no communication delay. A velocity control is used to adjust the ETAs of individual UAVs as follows

\[ \dot{v}_i = f_i(ETA_{N_i}) \]  

where, \( N_i \) denotes the set of neighbors of \( U_i \), and the function \( f_i \) is given as

\[ f_i(ETA_{N_i}) = ETA_i - \frac{1}{|N_i|} \sum_{j \in N_i} ETA_j, \quad i = 1, \ldots, N \]  

with the estimated arrival time for \( U_i \) denoted as \( ETA_i \). As is true for a realistic fixed wing UAV, it is assumed that the UAVs have velocity bounds, that is,

\[ v_{min} \leq v_i \leq v_{max} \quad i = 1, \ldots, N \]  

If the deviations of UAVs due to collision avoidance maneuvers are small, then the velocity control as given in Eq. (4) will suffice to achieve rendezvous. However, there might be cases where the avoidance maneuvers will cause significant changes in ETAs. In those cases, use of only a velocity control will lead to saturation, that is, upper and lower bounds of the velocity will be reached while the required ETA is still unachieved. To account for such cases, the following strategy is proposed. Whenever the lower velocity bound is reached and a UAV cannot further increase its ETA by reducing velocity, it does a ‘wandering maneuver’. The wandering maneuver consists of turning and moving away from the target. The wandering maneuver is continued until the required ETA is attained.

To compute the required velocity rate as in Eq. (4), it is necessary for a UAV to estimate its ETA to the target which is the rendezvous point. It is assumed that all UAVs turn with a minimum radius of \( \min R \). To arrive at the rendezvous point as quickly as possible, the UAVs follow a Dubins path (Dubins, 1957) from their current location to the rendezvous point. To find the ETA of a UAV following a Dubins path, two cases (shown in Fig. 1) need to be considered. In case (a), the target is on the left of the UAV
and in case (b), the target is on the right of the UAV. In both the cases, a circle tangent to the velocity vector of the UAV is drawn toward the target. This paper considers only those cases where the UAVs start sufficiently far away from the target, and therefore, this circle will not encircle the target. For case (a), the center of this circle \((x_c, y_c)\) for a UAV \(U_i\) is given as

\[
x_c = x_i - R_{\text{min}} \sin \psi_i
\]
\[
y_c = y_i + R_{\text{min}} \cos \psi_i
\]

and for case (b), it is

\[
x_c = x_i + R_{\text{min}} \sin \psi_i
\]
\[
y_c = y_i - R_{\text{min}} \cos \psi_i
\]

To calculate the distance that the UAV has to travel along the circle till the tangent point, the angles \(\theta_1\), \(\theta_2\), and \(\theta_3\) are defined as shown in Fig. 1. For both cases (a) and (b), \(\theta_1\) and \(\theta_2\) are given as for case (a) as (refer Fig. 1(a))

\[
\theta_1 = \arctan \left( \frac{y_T - y_c}{x_T - x_c} \right)
\]
\[
\theta_2 = \arccos \left( \frac{R_{\text{min}}}{\sqrt{(x_T - x_c)^2 + (y_T - y_c)^2}} \right)
\]

where \((x_T, y_T)\) is the target location, and \(\theta_3\) for case (a) is

\[
\theta_3 = \frac{\pi}{2} - \psi_i
\]

and for case (b) as (refer Fig. 1(b))

\[
\theta_3 = \frac{\pi}{2} + \psi_i
\]

Now, the ETA of \(U_i\) to the target can be obtained as

\[
ETAI_i = \frac{D_i}{v_i}
\]
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2.1 Simulations

The efficacy of the proposed rendezvous via consensus algorithm is shown through simulations. Fig. 2 shows a case of two UAVs where consensus is reached on their ETAs by adjusting the velocities of the individual UAVs. For this and other simulations, a minimum radius of turn of 50 m was used for the UAVs unless otherwise specified. For all the simulations in this paper, the UAVs have an initial velocity of 15 m/s. The figure shows the trajectories of UAVs, and the variation of their velocities and ETAs with time. In this case, as seen in Fig. 2, none of the UAVs hit the velocity bounds en route rendezvous.

Fig. 3 shows a case of rendezvous of two UAVs starting at arbitrary locations with arbitrary orientations, where UAV $U_1$ hits the lower velocity bound and does a wandering maneuver to increase its ETA while $U_2$ hits the upper velocity bound. For simulations in this paper, it is assumed that the upper and lower velocity bounds are 10 and 20 m/s. A wandering maneuver of a UAV, as described earlier, consists
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Figure 3: Rendezvous of two UAVs, $U_1$ and $U_2$, using velocity control and a wandering maneuver by $U_1$ of a turn in the direction opposite to what would have taken it to the rendezvous point. Fig. 3 clearly shows the increase in ETA of $U_1$ with the wandering maneuver.

Fig. 4 shows 10 UAVs starting at arbitrary locations with arbitrary orientations using the consensus based algorithm to achieve rendezvous. The time evolution of their ETAs and velocities are also shown in the figure.

Note that unlike the traditional consensus, where all the agents converge to a constant consensus value, in the present case, the consensus value of the ETA to target changes with time. In fact, it decreases as UAVs approach the rendezvous point. Also note that since rendezvous of multiple UAVs to a point in space will cause a collision among them, it is assumed that the UAVs will make a split maneuver when they reach within a specified radius of the rendezvous point.

3 Tracking a Target using the Rendezvous Algorithm

The rendezvous, as described in the previous section, is achieved by the UAVs via velocity control obtained through a consensus on their ETAs. In that case, although a consensus is reached, the ETAs of UAVs continuously decrease as they approach the target or the rendezvous point (see Figs. 2 to 4). However, if one of the UAVs has a constant ETA, the consensus algorithm will cause the ETAs of the other UAVs too to converge to that value. As a constant ETA to a target implies a constant distance from that target, a UAV having non-zero velocity and a constant ETA to target, will necessarily encircle the target. Thus, target tracking from a constant standoff distance can be achieved by the introduction of a virtual UAV
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Figure 4: Rendezvous of 10 UAVs using velocity control within bounds and wandering maneuvers that has a constant ETA.

To demonstrate this, an example of a couple of UAVs tracking a stationary target is shown in Fig. 5, where a third UAV with a constant ETA of 30 seconds acts as the virtual UAV. All the UAVs, virtual and otherwise, execute the proposed rendezvous algorithm. As seen in Fig. 5, UAV $U_1$ is away from the final circle for standoff tracking while $U_2$ is inside it. Therefore, $U_2$ does a wander away maneuver while at the same time it decreases the speed to its lower bound. The UAV $U_1$, whose ETA is higher than 30 s, turns and moves toward the target increasing its speed. As $U_1$ moves toward the target its ETA will decrease. When the ETA of $U_1$ is below 30 s, which happens at around 30 s in this simulation, its speed decreases so as to keep the ETA constant at 30 s. When the speed of $U_1$ reaches the lower bound, its ETA starts to decrease which is the reason for the dip in the ETA at around 40 s from which the UAV recovers by turning away from the target. From then onwards, the UAVs switch between turning toward and away from the target at a frequency such that a constant ETA of 30 s is maintained. This behavior causes the UAVs to track the target from a standoff distance. This is shown in Fig. 5. From the figure it is observed that the ETAs of all the UAVs converge to 30 seconds resulting in them circling around the target.

Given the ETA of the virtual UAV, $\text{ETA}_{\text{virtual}}$, the standoff radius or the tracking radius can be found as

$$R_{\text{standoff}} = v_{\text{min}} \text{ETA}_{\text{virtual}} - \left( \frac{\pi}{2} - 1 \right) R_{\text{min}}$$

(16)

This can be easily obtained from the illustration given in Fig. 6 and from the fact that the UAVs circle around the target with a speed of $v_{\text{min}}$. Similarly, given a standoff radius $R_{\text{standoff}}$, it is possible to find
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Figure 5: Two UAVs tracking a stationary target with a constant ETA of 30 s

the ETA of the virtual UAV that will cause the other UAVs to circle the target with that standoff radius as

\[ \text{ETA}_{\text{virtual}} = \frac{R_{\text{standoff}} - R_{\text{min}}}{v_{\text{min}}} + \frac{\pi R_{\text{min}}}{2 v_{\text{min}}} \]  

(17)

Fig. 7 shows another example of target tracking where the ETA of the virtual UAV is chosen such that the UAVs \( U_1 \) and \( U_2 \) track the target with a standoff radius of 500 m. Both the UAVs start from outside the desired circle and using the proposed algorithm, converge to the desired tracking circle.

The explanation for the tracking behavior of UAVs with the introduction of a virtual UAV with constant ETA is as follows. Since there is a UAV (the virtual UAV) the ETA of which stays constant, all

Figure 6: Illustration of a UAV tracking a target with constant ETA or standoff radius
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Figure 7: Two UAVs tracking a stationary target with a standoff radius of 500 m

other UAVs first try to increase their respective ETAs to match that of the virtual UAV by decreasing their velocities. This is assuming that the initial ETAs of the other UAVs are higher than that of the virtual UAV. Once the velocities hit the lower bound, these UAVs begin to perform the wandering maneuver. The wandering maneuver will cause the ETAs of the UAVs to increase beyond $ETA_{virtual}$ which cause them to maneuver towards the target resulting in reduction of ETA to values below $ETA_{virtual}$. This reduction will cause the UAVs to perform the wandering maneuver again and this switching process continues. It is this switching between the maneuvers towards and away from the target that causes a UAV to move in a circle around the target.

The change of ETAs of UAVs $U_1$ and $U_2$ corresponding to Fig. 7 is shown in Fig. 8. Initially, the UAVs are outside the circle to be tracked and therefore have ETAs higher than the required ETA. This makes the UAVs to turn and move toward the target which, in turn, causes a decrease in their ETAs (approximately till 10 s in Fig. 8). When the ETAs of UAVs $U_1$ and $U_2$ fall below the desired value, their speeds decrease causing their ETAs to slowly increase although the UAVs are moving closer to the target. This behavior is seen in Fig. 8 approximately from 10 s to 30 s. Once the speeds of the UAVs hit the lower bound, the ETAs suddenly decrease as the UAVs begin to move toward the target with a constant speed. This causes the ETAs to decrease (from 30 s to 40 s in Fig. 8) which triggers a wandering maneuver that will cause the UAVs to move away from the target causing an increase in the ETAs (this corresponds approximately to 40 s to 50 s in Fig. 8). Further, as described above, a switching between maneuvers towards and away from the target occurs. The chatter, responsible for the tracking behavior, in the ETA plots of the UAVs is enlarged and shown as an inset in Fig. 8.
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Figure 8: Chatter in the achieved ETAs of UAVs enabling them for a standoff tracking of target

Although the rendezvous algorithm developed in this paper can be used for target tracking via the introduction of a virtual UAV, it may not be a practically feasible solution as the tracking behavior is achieved through a high frequency switching between right and left turns, as described above, which can be very costly. In simulations, a perfect tracking is achieved as vindicated by the examples given above. In practice, one can reduce the demanded switching frequency, in which case the tracking will not be perfect. Also, in many practical applications, a tracking with precisely constant standoff radius may not be required. In that case, the UAV will execute a mild oscillatory motion about the circle of specified standoff radius.

The same approach can be used to track a moving target with a constant standoff distance by using the current position of the target as the point of rendezvous during every time step. Fig. 9 shows two UAVs having minimum radii of turn of 50 m each tracking a slowly maneuvering target. The target does a slow sinusoidal maneuver with a speed of 2 m/s. The UAVs have a constant airspeed of 15 m/s. From the relative frame of the target, it would appear that the UAVs are circling around the target in a circle with a standoff radius of 150 m. Fig. 10 shows two UAVs tracking a target moving in a straight line with a constant speed of 5 m/s. Although the paths of the UAVs appear helical in the inertial frame, in the relative frame of the target, the UAVs would appear to the target as circling around it with the desired constant standoff radius which is 500 m in this case. Figs. 9 and 10 show the trajectories of the target as well as that of the UAVs.
Figure 9: Two UAVs tracking a slowly maneuvering target moving with a speed of 2 m/s with constant standoff radius

Figure 10: Two UAVs tracking a target moving with a speed of 5 m/s with constant standoff radius
4 Rendezvous with Collision Avoidance

This section will show that the rendezvous algorithm that was developed in this paper can be used to achieve rendezvous under collision avoidance.

4.1 Incorporating Collision Avoidance

UAVs trying to rendezvous at a point need to avoid other UAVs on their way. Toward this, the multiple UAV collision avoidance algorithm developed in ? (?) is used. This algorithm is briefly discussed below. The collision avoidance algorithm consists of applying lateral accelerations to increase the line of sight (LOS) rate between UAVs that are on a collision course. When a UAV detects multiple conflicts, it selects a UAV from among those of its neighbors with which its predicted Zero Effort Misses (the miss distance that will result if both the UAVs continue in their current course) are less than the minimum desired separation. The UAV selected is the one with which the collision is imminent, that is, the expected time of collision is the earliest. The UAV then pulls out of the collision course by applying a lateral acceleration in a way that will increase the rate of rotation of the LOS connecting the two UAVs. This is illustrated in Fig. 11. To increase the LOS rate in this scenario where $\theta_2 > \theta_1$, accelerations $a_1$ and $a_2$, which make the UAVs perform the tightest turns, are applied to $U_1$ and $U_2$, respectively, in the directions as shown in Fig. 11. If a UAV is not in collision course with any other UAV, then it applies the turn rate and acceleration commands for rendezvous as in Eqs. (3) and (4).

4.2 Simulation Results

For the simulations, global communication between UAVs is assumed. However, a local communication, as imposed by limited communication range constraints of UAVs, will also work equally well as long as the underlying communication graph is connected. Fig. 12 shows rendezvous of 5 UAVs where three of them avoid collisions with other UAVs on the way to rendezvous. The UAVs in this simulation have a minimum turn radii of 100 m. It is assumed that the other UAVs in free flight (non rendezvousing UAVs) are non-
cooperating and do not perform collision avoidance maneuvers. The rendezvous algorithm is seen to aid rendezvous even when the UAVs perform collision avoidance maneuvers to avoid the trajectory conflicts. Fig. 13 shows that the collision avoidance maneuvers causes changes in ETAs of the corresponding UAVs but are promptly nullified by the consensus protocol to guarantee a rendezvous.

Another test case is performed where a group of UAVs have to attain rendezvous with collision avoidance in the presence of very high velocity (50 m/s) non-cooperating obstacles in the environment. The resultant trajectories in a sample scenario where six UAVs are required to achieve rendezvous are shown in Fig. 14. The wiggles in the trajectories are due to the avoidance maneuvers. In this case too, no collisions were observed and rendezvous was achieved in spite of the collision avoidance maneuvers.

5 Summary and Conclusions

This paper addressed the problem of rendezvous of multiple UAVs when the UAVs have to perform collision avoidance maneuvers en route rendezvous. An algorithm was proposed in which the UAVs communicate with each other and iteratively arrive upon a common estimated time of arrival at the rendezvous point using a consensus algorithm. The individual UAVs, in cases where detours caused by collision avoidance maneuvers, modify their arrival times at the rendezvous point through velocity control prescribed via consensus on the estimated arrival times and a wandering maneuver, if necessary. The simulations that are presented demonstrate the efficacy of the proposed rendezvous algorithm. It was shown that by the incorporation of a virtual UAV, the rendezvous algorithm can be modified to
Figure 13: The ETAs of UAVs while attaining rendezvous in presence of collision avoidance

Figure 14: Six UAVs attaining rendezvous in presence of collision avoidance
track a target stationary or slowly maneuvering from a constant standoff distance. The current approach
requires frequent information exchange between the rendezvousing UAVs. Future research will focus on
rendezvous of multiple UAVs with intermittent information exchanges and communication delays.

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