UAV COLLISION AVOIDANCE VIA OPTIMAL TRAJECTORY GENERATION METHOD

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Abstract

A collision avoidance algorithm is described in the condition that an UAV circumvents designated targets which have their protected region. Considering generalized shape of the protected region, an ellipsoid is adopted to represent the possible geometries. For the collision avoidance algorithm, it is assumed that en route UAVs are linked by real time data bases like ADS-B and pre-determined geographical feature information is available. With the conditions, all UAVs know the environmental information for their ongoing path. The information for the other targets' positions and velocities are used to expect a conflict or collision for one UAV and the UAV maneuvers not to intrude the other targets protected region. The avoidance algorithm is used to generate a reference trajectory between ongoing position and the instant for the targets passed away. The possible trajectories between the points for the start of avoidance and passed by are tracked. For the case of multiple conflict targets, determining the priority in accordance with predicted conflict times for the targets, the avoidance direction is determined to resolve the conflict situation sequentially.

1 Introduction

The conception for 'Free Flight' [1] has taken main issue for UAV mission implementation and it is popularly generalized these days as the traffic of UAVs is growing. To realize the purpose, many preliminary researches are performed. For the collision detection and alerting, it is general for aircraft to facilitate TCAS or GPS-based traffic display system [2-4]. Therein, to alert the traffic condition, ADS-B is essentially considered to transmit and correspond to their en route information. The word 'conflict' can be defined as a "predicted violation of a separation assurance standard" [3]. If two vehicles encounter each other where the 'conflict' has to be resolved, the vehicles are to maneuver not to intrude certain protected region for each other. Therefore, for the 'Free Flight', it is very essential task to understand geometric relations between two vehicles in a conflict. One may determine a conflict condition by simply calculating CPA(Closest Point of Approach) and the relative distance at that point as in [5]. As an extension of the previous studies described above, our research group has attempted to propose schemes to resolve the conflict between aircrafts or UAVs. The methods are based on the probabilistic motion-based approach and the geometrical relation-based approach for the conflict detection and resolution [6, 7].

On the other hand, an UAV may face obstacles such as mountain and big structure during its mission implementation. The geographical feature or artificial construction is not dynamic target, but still an obstacle to avoid. When assuming the protected regions for static or dynamic obstacles are pre-designated, many trajectories from starting point to goal position are generated under the consideration of the protected region for targets which are on the possible paths for one UAV.

In this paper, to embody the protected region for target, a figure of ellipsoid is used and all targets are summed to have an assurance standard volume expressed by certain part of an ellipsoid as their protected region. If an UAV is on route for task implementation, the UAV accesses the environmental information for target's position (and velocity for dynamic target) linked by a real-time data or pre-provided data related with geographical information. After recognition of the 'conflict' situation, the procedure is accomplished to extract an optimal trajectory to resolve the violation in an effective way. First of all, the direction for avoidance is determined and a reference trajectory to graze the firstly upcoming target is obtained.

2 Dynamic Modeling

In this paper, it is assumed that all dynamic targets and our UAV which performs its task keep their constant velocities and are regarded as point mass. Of dynamic targets only UAV is our consideration for target generation. The dynamics of our UAV is defined as follows.

$$\begin{aligned} \dot{x} &= V_H \cos\gamma \\ \dot{y} &= V_H \sin\gamma \\ \dot{z} &= V \sin\theta = V_V \\ \dot{\psi} &= \frac{g \tan\phi}{V_H} \end{aligned} \tag{1}$$

where V_H, V_V, ψ, θ, and ϕ are horizontal and vertical velocities, heading, pitch, and bank angles respectively. Here, the bank angle and pitch angle follows 1st order delayed equation by command.

$$\dot{\phi} = \frac{1}{\tau_\phi}\left(\phi_{com} - \phi\right) \tag{2}$$

$$\dot{\theta} = \frac{1}{\tau_\theta}\left(\theta_{com} - \theta\right) \tag{3}$$

Eq. (2) and (3) implies the actuation system delay with 1st order lag time constant.

3 Geometric Relation

3.1 Ellipsoid protected region

The protected region is regarded as an ellipsoid volume. In the previous studies, the protected region concept is employed to determine an assurance zone secured [1,3,5,6]. The shapes are varied with respect to approaches and their applications. In this paper we assume that the protected region takes an ellipsoidal volume such that most of variable volumetric objects are embodied. The objects can be a target UAV, a geographical feature, or any kind of artificial construction.

From the assumption of ellipsoid, an example scenario on the way of our UAV can be shown as in Fig. 1. In the scenario, Our UAV has to resolve a conflict with the target UAV en route path.

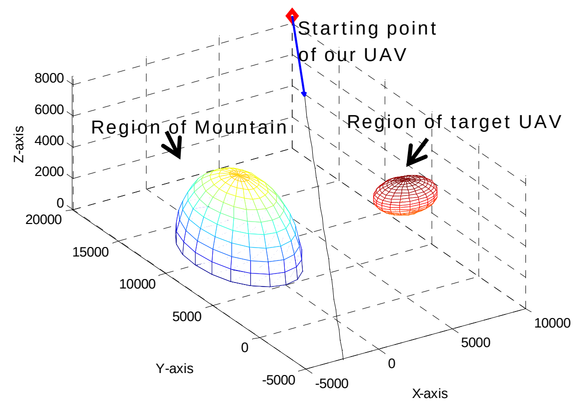


Fig. 1. One possible simulation condition with targets

To formulate the conflict situation in a geometrical relation, we consider a relative motion onto the target. If the target ellipsoid center is located at the origin in the relative frame, the ellipsoid surface equation is given as

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1 \tag{4}$$

Here, a, b, and c indicate the ellipsoid semi-axis lengths, and a vector (x, y, z) is arbitrary position in relative coordinate. To determine the 'conflict' condition with targets, relative positions and velocities are required. From the given relative position and velocity information, a line equation can be derived.

$$\frac{x - x_r}{u_r} = \frac{y - y_r}{v_r} = \frac{z - z_r}{w_r} = \tau_{rel} \tag{5}$$

where (x_r, y_r, z_r) is relative position from the target, and (u_r, v_r, w_r) indicates the relative velocity. On the other hand, if this line passes through the target's ellipsoid volume, the surface equation of ellipsoid, Eq. (4), and the line equation, Eq.(5), have two real number solutions for τ_{rel}. Here, τ_{rel} is the time of crossings of relative trajectory (Fig. 2).

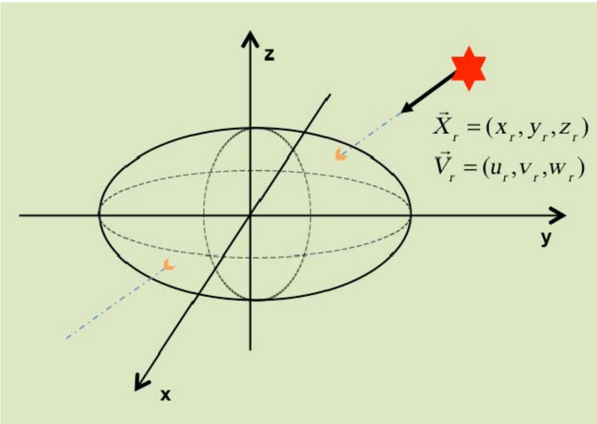


Fig. 2. Relative motion from a target position

When we consider the conflict where our UAV go through the target UAV's protected region as in Fig. 2, the solution for τ_{rel} is obtained in the relation below.

$$\begin{aligned}&\left(\frac{u_r^2}{a^2}+\frac{v_r^2}{b^2}+\frac{w_r^2}{c^2}\right)\tau_{rel}^2\\&+2\left(\frac{u_r x_r}{a^2}+\frac{v_r y_r}{b^2}+\frac{w_r z_r}{c^2}\right)\tau_{rel}\\&+\left(\frac{x_r^2}{a^2}+\frac{y_r^2}{b^2}+\frac{z_r^2}{c^2}-1\right)\\&=A\tau_{rel}^2+2B\tau_{rel}+C=0\end{aligned} \tag{6}$$

Here, $B \le 0$ indicates upcoming condition, and $B^2 - AC \ge 0$ means conflict.

3.2 Minimum avoidance direction

To avoid the 'conflict', our UAV must have a trajectory not into the target ellipsoid. From the relation in Eq. (6), the grazing points on target's ellipsoid can be selected when $B^2 - AC = 0$ which means one real value of τ_{rel}. And the possible solution points on the target ellipsoid via $B^2 - AC = 0$ forms a connected line. The direction vector from our UAV position to one of the points yields the grazing trajectory. In this paper, for efficient maneuver, a point on the closed line is selected and a reference trajectory is determined from our UAV's position to that point so as to make minimum direction difference between original direction and that of the reference trajectory. Figure 3 shows the required straight trajectory for minimum avoidance direction when a 'conflict' is detected.

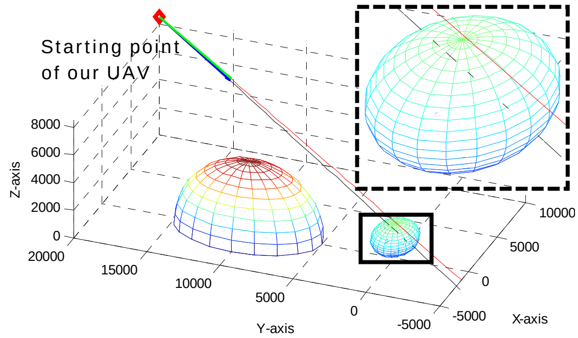


Fig. 3. Minimum direction avoidance

The solution shown in Fig. 3 is obtained by resolving the following optimization problem. An optimization problem to find minimum direction vector can be described as follows.

Objective :

To find a velocity vector $\vec{V}_* = (u_*, v_*, w_*)$ such that it yields a minimum angle avoidance trajectory which grazes the protected region.

Formulation :

$$\max\ J = (u_r, v_r, w_r)\bullet(u_*, v_*, w_*) \tag{7}$$

subject to

$$\begin{aligned}&C_1 := B^2 - AC = 0 \text{ for vector } (u_*, v_*, w_*)\\&C_2 := u_*^2 + v_*^2 + w_*^2 - 1 = 0\end{aligned} \tag{8}$$

Finding zeros of the Jacobian of Hamiltonian shown in Eq. (9) with five unknowns u_*, v_*, w_*, λ_1, λ_2 resolves the optimization problem described in Eqs. (7) and (8).

$$H = (u_r, v_r, w_r)\bullet(u_*, v_*, w_*) + \lambda_1 C_1 + \lambda_2 C_2 \tag{9}$$

The Jacobian matrix of Eq. (9) for the vector (u_*, v_*, w_*) is given as follows.

$$\begin{aligned}\frac{\partial H}{\partial u_*} &= u_r + \lambda_1 \frac{\partial C_1}{\partial u_*} + \lambda_2 \frac{\partial C_2}{\partial u_*} = 0\\ \frac{\partial H}{\partial v_*} &= v_r + \lambda_1 \frac{\partial C_1}{\partial v_*} + \lambda_2 \frac{\partial C_2}{\partial v_*} = 0\\ \frac{\partial H}{\partial w_*} &= w_r + \lambda_1 \frac{\partial C_1}{\partial w_*} + \lambda_2 \frac{\partial C_2}{\partial w_*} = 0\end{aligned} \tag{10}$$

Equation (10) indicates the necessary condition of optimal solution. Finally, with five equations within Eq. (8) and (10), the five unknowns can be solved by any kind of optimization method. In this paper, the solution is given by a temporary optimization via an embedded function of *MATLAB optimization tool*.

4 Multiple-Target Avoidance

The scheme for the pairwise conflict resolution has been shown in section 3. And the pairwise scheme is extended to the case for multiple-target avoidance. In this paper, we suggest a sequential algorithm to resolve the condition with multiple conflicts. Firstly, we consider the first two conflicts. The expected times of all conflicts can be evaluated by applying Eq. (6) to all targets. Of all conflicts, the early two conflicts are our first concern. Here, the direction vector for minimum avoidance of each conflict is obtained. From vector sum of them, we can predict the next step direction of our UAV. As shown in Fig. 4, we iterate the same procedure to derive the final direction to avoid the two conflicts. When the iteration is performed with very short time terms as our UAV is guided to a recommended direction vector during the flight, the solution are converged to the contact point of two projected ellipses. As a result, we can guide our UAV to the finally converged optimal point of avoidance where the optimal point is the contact point as easily inferred in Fig. 4. However, all conflict geometries are not resolvable. If the curvatures of tangent of the projected ellipses are less than those of corresponding circles with same radius and the two vectors of the conflicts are parallel to each other, then the solution from adding them up is remains in the straight line (Fig. 5). In this paper, when the solution is unresolvable, some arbitrary disturbed direction is preferentially applied and then the algorithm may be functional.

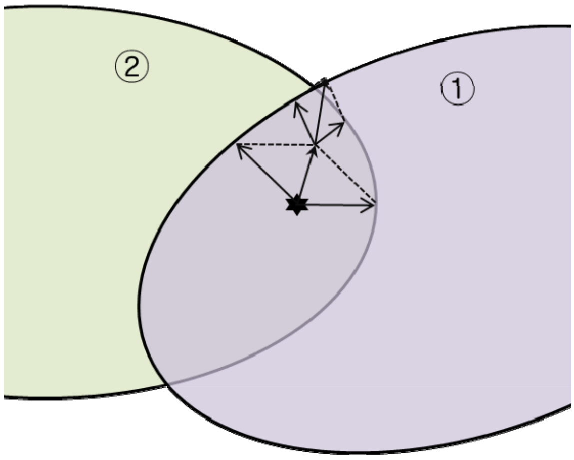


Fig. 4. Convergence of avoidance direction

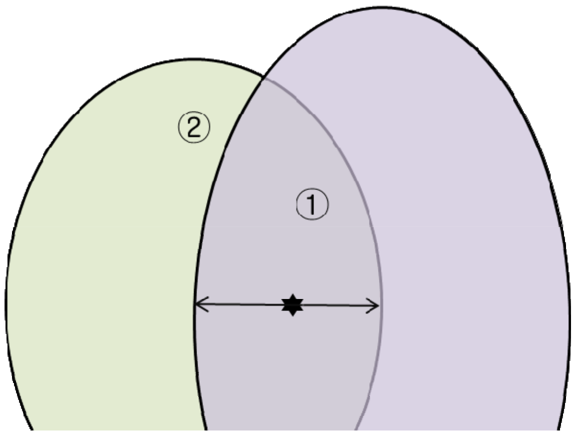


Fig. 5. An example of unresolvable geometry

5 Track of Reference Trajectory

When the desired direction is given by avoidance algorithm, the reference trajectory is the straight line of the vector.

The track of reference trajectory for UAV can be performed properly as designing any kind of controller. The controller calculates bank/pitch command such that the UAV maneuvers following the dynamics given in section 2. Also, the absolute value of the velocity of the UAV is assumed to be constant by a velocity hold controller.

The procedure of designing the controller is not differed from general approaches, so it is omitted in this paper.

6 Numerical Simulation

In this section, two simulation scenarios are considered. The first one is a pairwise case where our UAV senses just one conflict with a target. The second one is the case that our UAV senses a couple of conflicts and the proposed algorithm in section 4 is applied to avoid upcoming targets.

6.1 Pairwise case

For the pairwise case, the target is assumed to have constant velocity to its goal position somewhere to the direction of the velocity.

The initial conditions of our UAV and the target are given as follows.

<u>Initial condition :</u>

< Our UAV >

$$\vec{X}_o = (10, 20, 7)\ (km)$$

$$\vec{V}_o = (-70, -130, -115)\ (m/s)$$

< Target 1 >

$$\vec{X}_{t1} = (0, 0, 0)\ (km)$$

$$\vec{V}_{t2} = (30, 70, -50)\ (m/s)$$

Also, the semi-axis dimension of the protected region of target 1 is given below.

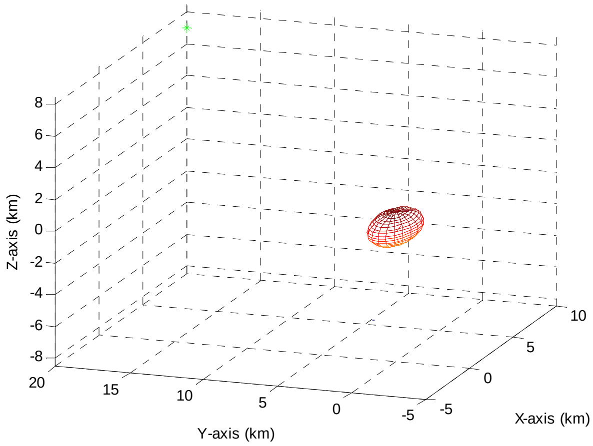
<u>Ellipsoid dimension of target 1 :</u>

<Semi-axes for x, y, z >

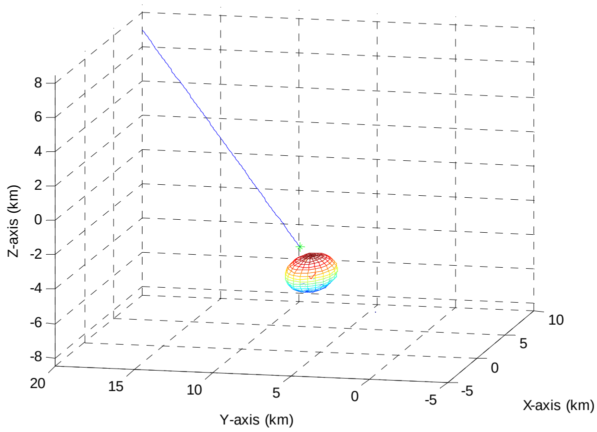
$$(a1, b1, c1) = (2.0, 1.5, 1.0)\ (km)$$

From described initial condition and protected region of target 1, the predicted time of conflict is about 96 second. And the simulation results are shown in Figs. 6 and 7.

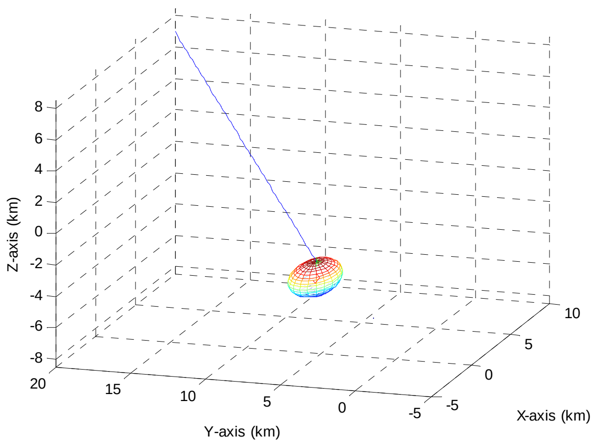
From the result, it is shown that our UAV successfully resolve the conflict. The line of trace shows the path of our UAV. In Fig. 7, the miss distance from the nearest point of the surface of the protected region to our UAV is recorded. From the record, it is inferred that Our UAV has not intruded target's protected region and it grazed the surface of it. Also, as avoiding the target, the time for minimum miss distance occurs at around 98 sec.



(a) Initial encounter condition at 0 sec



(b) Trace of our UAV at 90 sec



(c) Trace of our UAV at 98 sec

Fig. 6. Trace of our UAV for pairwise case

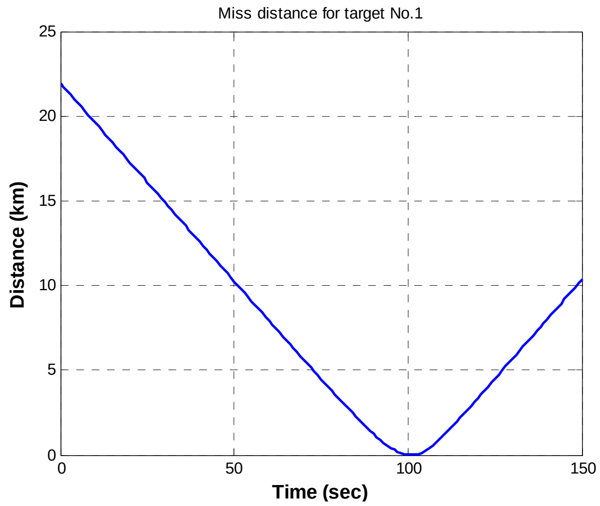


Fig. 7. Miss distance form our UAV to target protected region (km)

6.2 Conflict with two objects

In this subsection, we consider an additional target which is stationary with zero velocity. The initial condition and the dimension of its protected region are given below.

Initial condition of target 2 :

< Target 2 >

$$\vec{X}_{t2} = (0, 15, -60)\ (km)$$

$$\vec{V}_{t2} = (0, 0, 0)\ (m/s)$$

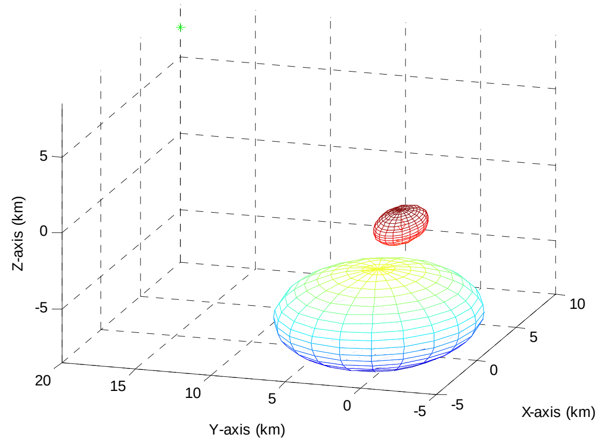
Ellipsoid dimension of target 2 :

<Semi-axes for x, y, z >

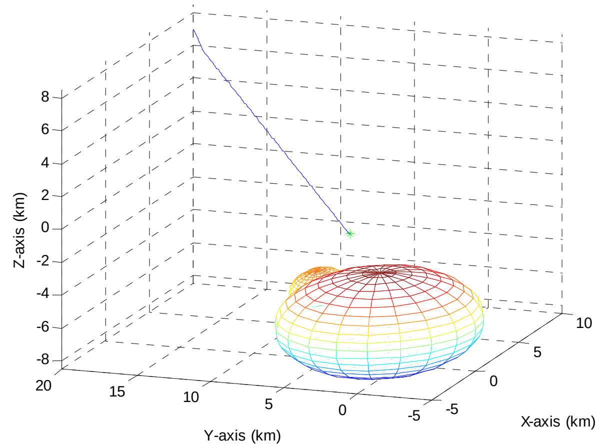
$$(a2, b2, c2) = (5.0, 6.5, 3.0)\ (km)$$

In this scenario, our UAV predicts a couple of conflicts and the times of occurrence of conflicts are about 96 and 104 second respectively.

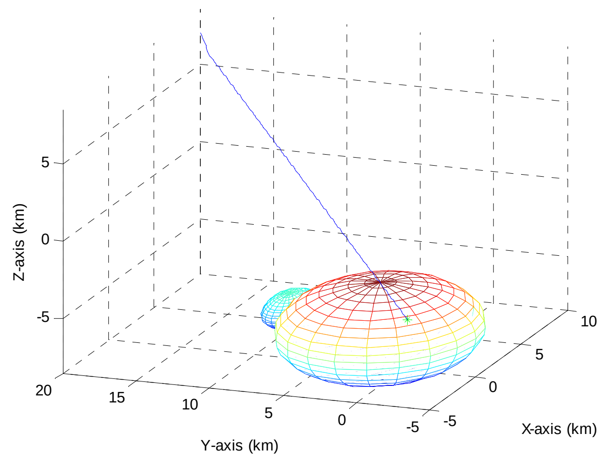
The simulation results are shown in Figs. 8-10. Figure 8 lets us know the avoidance is accomplished successfully and our UAV finally grazes the second target surface. In this scenario, our UAV had to change its original flight path with larger turn angle than the first scenario only with target 1. Also, form the results in Fig. 9 and 10, to avoidance all conflicts, the maneuver apparently weights on the second target avoidance. The minimum miss distance for target 1 is about 3.8 km at about 93 second and our UAV passes by target 2 with about 0.03 km at around 145 second.



(a) Initial encounter condition at 0 sec



(b) Trace of our UAV at 110 sec



(c) Trace of our UAV of blue line at 150 sec

Fig. 8. Trace of our UAV for conflicts with two objects

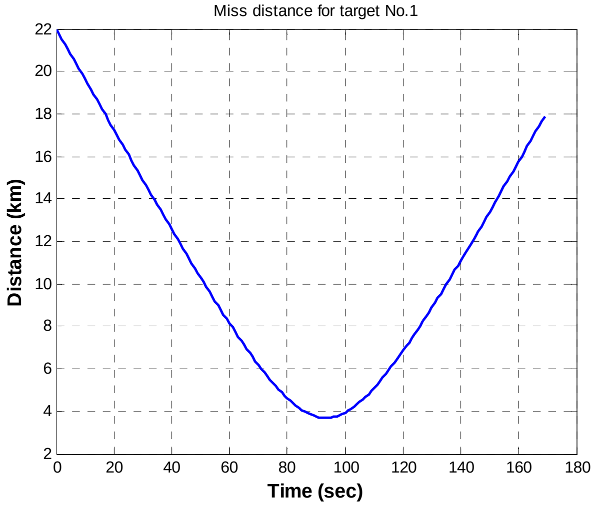


Fig. 9. Miss distance form our UAV to the protected region of target no.1 (km)

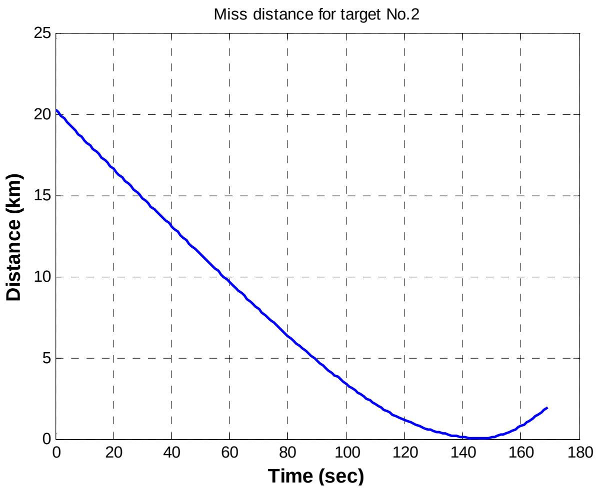


Fig. 10. Miss distance form our UAV to the protected region of target no.2 (km)

7 Conclusion

In this paper, an algorithm on the avoidance of conflict between our UAV and certain kind of target is presented using geometric relation. The protected regions of targets are assumed to form ellipsoidal geometry. Additionally, it is assumed that our UAV maneuvers defensively to the targets; it is guided to a direction not to intrude the protected region. The guidance direction of our UAV is given as an optimization solution with minimum avoidance direction angle. Also, for the multiple-target case, our UAV takes an action for the first two predicted conflicts, which is simulated in this paper.

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