The Trajectory Generation of UCAV Evading Missiles Based on Neural Networks

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Abstract. In order to solve the problem of evading air-to-air missiles of UCAV in autonomous air combat, the flight dynamics model and 3-dimensional guidance trajectory model based on proportional guidance were established and performance constraint conditions of missiles were constructed. According to the definition of basic maneuver library, 72 kinds of avoidance maneuvers were constructed. All 72 avoidance maneuvers were simulated while UCAV was at different relative yaw angles and relative pitch angles, and the optimal avoidance maneuvers under the corresponding conditions were selected out. Training samples and test samples were constructed by utilizing the acquired data, and the neural network for generating control parameters was trained. Under different conditions, neural network method and random selection method were simulated. The results show that the success rate of escape of the proposed method is higher and the time cost of generating the control parameters is less, which meets the requirements of effectiveness and real-time.

1. Introduction
Autonomous air combat capability is an essential capability for future UCAV. Since there is no need to consider the physiological conditions of the pilot, UCAV has better maneuverability and can replace human beings in dangerous environments. However, with the gradual improvement of air-to-air missile performance, the ability of combat aircraft to survive in the air battlefield is decreasing rapidly. In traditional air combat, pilots usually rely on their own experience to choose evasive maneuvers. But facing missiles with far more maneuverability than fighter, it is difficult for pilots to choose appropriate maneuvers under great psychological pressure, whereas UCAV can choose effective maneuvers to survive through its strong abilities of data analysis. Meanwhile, UCAV does not need to consider the limitations of the pilot's physiological conditions.

Reference [1] shows that fighter with roller maneuver against missiles has more advantages. Maneuver of UCAV to escape from proportional guided missile has been addressed in [2] and the strategy of evading missiles has been presented in [3] given the information of missile movement. In [4], an effective missile avoidance strategy based on neural network has been designed for UCAV, which combines the current relative position of the aircraft and the basic maneuver library. Differential games has been utilized for maneuver of fighters against missiles in [5] and nonlinear model predictive control has been used in [6] to make fighter escape from the attack of missile. The effects of initial distance and direction of maneuver on escape success rate have been studied quantitatively in [7]. UCAV with thrust vector randomly chooses the escape strategy of typical maneuverable evading missile with a certain probability has been presented in [8], however, thrust
vector engines are not widely used yet. In [9], the force of missile at a certain point in space has been constructed using the information of missile movement and the direction the differential of the force has been regarded as maneuver evasive direction. The influence of sinusoidal maneuver, u-shaped maneuver and decoy projectile on evading missile has been studied in [10]. However, no work has been done on maneuver library and the majority of them choose maneuvers randomly. In order to enhance the success rate of evasion, the strategy of UCAV evading missiles based on neural networks was presented. The major contributions of this study are summarized as follows: 1) Based on the model of UCAV and missile motion dynamics, 72 evasive maneuvers are constructed. 2) 756 UCAV initial states composed of different relative yaw angles and relative pitch angles are constructed and 72 maneuvers in each state are simulated. Thus, we can get the optimal evasive maneuver in the corresponding state. 3) Based on the data acquired, the neural network from UCAV current situation to maneuvering control quantity has been constructed, which decreases time consumption.

2. Model of UCAV and missile
To simplify the complexity of the problem, the angle of attack and sideslip are not considered. And the UCAV motion dynamics model adopts normal overload, tangential overload and roll angle as control parameters. The formula is as follows:\(^1\):

\[
\begin{align*}
\dot{x}_t &= v_t \cos \gamma_t \cos \psi_t \\
\dot{y}_t &= v_t \cos \gamma_t \sin \psi_t \\
\dot{z}_t &= v_t \sin \gamma_t \\
\dot{v}_t &= g(n_t - \sin \gamma_t) \\
\dot{\psi}_t &= \frac{g}{v_t} (n_t \cos \mu_t - \cos \gamma_t) \\
\dot{\gamma}_t &= \frac{g}{v_t \cos \psi_t}
\end{align*}
\]

\(v_t, \psi_t, \) and \(\gamma_t\) denote the velocity, yaw angle, and pitch angle respectively. \(g\) is gravity, \(\mu_t\) is roll angle. \(n_t\) and \(\eta_t\) denotes tangential overload and normal overload respectively. \((x_t, y_t, z_t)\) are the coordinates of UCAV in the inertial system. The dynamic equation of the missile is\(^2\):

\[
\begin{align*}
\dot{v}_m &= \frac{(P_m - Q_m)g}{G_m} - g \sin \gamma_m \\
\dot{\psi}_m &= n_{my} \cdot \frac{g}{v_m \cos \gamma_m} \\
\dot{\gamma}_m &= n_{mp} \cdot \frac{g}{v_m} - \frac{g \cos \psi_m}{v_m}
\end{align*}
\]

\(P_m\) and \(Q_m\) are the thrust and air resistance of the missile respectively. \(G_m\) is the mass of the missile. \(n_{my}\) and \(n_{mp}\) denote the overload in yaw and pitch direction of the missile respectively. The existing missiles generally use proportional guidance law to guide the system. As in [13], the guidance law in three dimensional space is decomposed into two perpendicular guidance laws in control plane. The overloads of the missile in yaw and pitch direction are defined as follows:

\[
\begin{align*}
n_{my} &= K \cdot \frac{v_m \cos \gamma_t}{g} [\beta + \tan \epsilon \tan(\epsilon + \beta) \dot{\epsilon}] \\
n_{mp} &= \frac{v_m K \dot{\kappa}}{g \cos(\epsilon + \beta)}
\end{align*}
\]
\( \beta \) and \( \varepsilon \) are line-of-sight deviation angle and line-of-sight pitch angle respectively. \( K \) is the coefficient of guidance law. There is an uncontrollable flight time \( t_0 \) after missile launch, during that time, the missile moves without power. And the lateral overload of the missile shall not exceed the limit \( n_{\text{max}} \). According to the actual use of tactical missile\(^{14}\), the performance of missile is subject to the following constraints: 1) Limitation of dynamic field angle. After launching, when the off-axis angle of the target is larger than missile dynamic field angle, the missile cannot continue to track the target. 2) Limitation of maximum flight time. When the flight time of the missile exceeds its maximum flight time, it destructs. 3) Limitation of minimum relative velocity of approach. When the distance between target and missile is less than 300 m and relative velocity of approach 250 m/s, the infrared sensor does not work properly.

3. The evasive strategy against missile

3.1 Avoidance maneuvers library

There are seven basic maneuvers of air combat as shown in figure 1. According to the definition of turn maneuver in the basic action library, different roll angles are selected to form the library of avoidance maneuvers. There are 72 maneuvers totally as showed in figure 2, by taking a roll angle at intervals of 5 degrees between -180 degrees and 180 degrees.

![Figure 1. Basic maneuver library.](image1)

![Figure 2. Avoidance maneuver library.](image2)

72 trajectories derive from 72 different roll angles, and their normal overloads and tangential overloads are selected according to the definition of turning maneuvers in the basic maneuver library. Considering the rotational speed of roll, the aircraft needs to roll from zero degrees, therefore, the graph composed of trajectories in the figure has an opening. And the greater rotational speed corresponds to the smaller the opening.

3.2 Neural networks for generating control parameters

There is a relative angle in three-dimensional space between UCAV axis and line-of-sight. It can be divided into relative yaw angle and relative pitch angle according to its horizontal and vertical projection\(^{15}\), and different relative angles correspond to different maneuvers. Considering the nonlinear mapping capability and real-time requirement, BP network is used to generate control quantity of evasive maneuver. Then the data needed by the training network is calculated. The relative angles are taken as input of the neural networks and the roll angles of UCAV are output of the neural networks. A total of 36 yaw angles are taken at intervals of 10 degree between 0 degrees and 360 degrees, and a total of 21 pitch angles are taken at intervals of 5 degrees between -50 degrees and 50 degrees. The 72 maneuvers in section 3.1 are simulated under each combination of samples. During the simulation, the missile axis always points to the target. From the successful escape maneuvers, the maneuver with the furthest distance of the missile when it misses its target is selected as the optimal evasive maneuver. If all maneuvers cannot escape under certain conditions, then select one at random.
4. Experiments and analysis
The maximum off-axis emission angle is 60 degrees and the maximum dynamic field angle is 70 degrees. The controlled flight time is 17 seconds and the maximum flight time is 27 seconds. The miss distance is 7 meters and the maximum overload is 40g. The initial velocity is Mach 0.8, the guidance coefficient in the control plane is 3, the simulation step is 0.01s. UCAV starts at Mach 0.5, its maximum velocity is Mach 0.8 and minimum velocity is Mach 0.26, roll angular velocity is 180 degrees/s. Maximum tangential overload and maximum normal overload is 5g.

4.1 Verifying avoidance maneuver library
The missile is initially located at \((0,0,5400)\) with its axis pointing towards the target. The UCAV is initially located at \((-2000,2000,5500)\), its initial yaw angle is 0 degrees, initial pitch is 135 degrees, and initial roll angle is 0 degrees. The blue line is the climbing trajectory of UCAV with a roll angle of 45 degrees and the red line is the tracking trajectory of the missile as showed in figure 3, and figure 4 shows the missile's overloads in pitch and yaw direction during tracking, figure 5 shows the change of the roll angle of UCAV during the escape process. figure 6 shows the relative yaw angle and relative pitch angle between missile axis and line-of-sight, it can be seen that the relative pitch angle between missile axis and line-of-sight exceeds 70 degrees at 10.8s after the simulation begins, so the missile missed its target.

4.2 Training neural networks
756 sets of data were calculated under the initial conditions in the previous section. After normalization, 650 groups were randomly selected as training samples and the rest were test samples. According to the empirical formula and after many attempts, it was found that networks performance was best when the number of nodes in the hidden layer was 4, therefore, the number of nodes in the
hidden layer was set as 4. Error curve of neural network was showed in figure 7. After several iterations, the training sample error converged. The test samples were inputted into the trained network and then got the outputs. The relative error of the outputs were calculated after inverse normalization as showed in figure 8. It demonstrated that the network could meet the application requirements.

![Figure 7. Error curves.](image1)

![Figure 8. Relative error of test samples.](image2)

4.3 Verifying algorithm performance

In order to verify the effectiveness of this method, it was simulated when UCAV was initially located at three different locations. Firstly, the initial relative yaw angle and relative pitch angle of UCAV were randomly generated. Then, the method in this paper and the method which selected maneuver randomly in the avoidance maneuver library were used to conduct experiments. Five sets of simulations were performed for each initial position and 100 times for each set. And the escape success rate of each group was calculated. Table 1 shows the escape success rate of UCAV when it was located at (-1500,1500,5500), (-2000,2000,5500), and (-2500,2500,5500) initially.

| Positions | Method       | Escape success rates (%) |
|-----------|--------------|--------------------------|
| 1         | Random       | 53  60  59  64  67       |
|           | Neural Network | 73  71  74  76  75       |
| 2         | Random       | 72  77  73  72  69       |
|           | Neural Network | 82  76  78  73  79       |
| 3         | Random       | 83  87  88  85  82       |
|           | Neural Network | 81  86  89  85  85       |

The escape success rate of neural network method was 14.4%, 5.0% and 0.2% higher than that of random selection method. We can infer that the escape success rate of random selection method decreases significantly when maneuver starts with the decrease of distance between the missile and the target, and the superiority of this method is mainly reflected in the moment when the initial distance between missile and target is small. Furthermore, the algorithm in this paper obtains that the calculation time of maneuver strategy is no more than 0.2s.

5. Conclusion

This paper aims to present a new maneuver decision method of UCAV evading missile. We have successfully achieved the aim by designing nonlinear mapping from current relative angles of UCAV to optimal evasive maneuver. First, we constructed 72 evasive maneuvers. Second, we conducted simulation experiments under various initial conditions and acquired the optimal maneuvers
correspond to different conditions. Third, a neural network was trained to generate maneuver through the relative angles of UCAV, which was able to choose evasive maneuvers quickly. In order to examine the performance of the proposed algorithm, we conducted a set of experiments. From the experimental results, we can conclude that this method has a higher evasive success rate and superiority when the initial distance between missile and target is small.

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