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INTENTION PREDICTION OF AERIAL TARGET UNDER INCOMPLETE INFORMATION

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Abstract. *Aiming at the Unmanned Combat Aerial Vehicle (UCAV) autonomous attack decision-making problem under the uncertainty and incompleteness of the modern battlefield information environment, an intention prediction method is developed for the aerial target based on improved grey incidence analysis method. To analyze the air combat situation, the angle, distance, velocity, altitude, energy and capability are introduced to determine the threat factors. Then, the weight is calculated by fuzzy inference, and the intention of aerial target is obtained by using grey incidence analysis method. Furthermore, the maneuvers of aerial targets are introduced to modify the prediction results. The simulation results show that the developed method can well realize the aerial target intention prediction under incomplete information.*

Keywords: Intention prediction, Grey incidence, Threat factors, Fuzzy inference

1. **Introduction.** With the widespread use of advanced technology in the field of military, information competition is very important in the 21st century [1]. Since the air combat environment has become increasingly complex, the demand of autonomous decision-making ability is also increased for air combat command and control system. In fact, the various advanced weapons are equipped, the air combat style is continuous innovating, and the complexity and unknown dynamic interference factors of modern battlefield environment are increasing. Predicting target intention in advance can help for the autonomous attack and defense decision-making of UCAV. On the other hand, predicting target intention in advance is benefit for improving the operational effectiveness of weapon system, and reducing the cost of the war. Thus, it is particularly important to predict the target intention before attack decision-making.

Target intention prediction is a complicated work. Some works can be found in the literature. Bayesian network was used to predict target intention in [2]. A method based on game theory was developed to predict target intention in [3]. A method was studied based on Dempster-Shafer (D-S) evidence theory for target intention prediction in [4]. In [5], an adaptive neuro-fuzzy inference system was introduced for the target intention prediction. Furthermore, the maximum similarity method was discussed to recognize the tactical intentions of the vessel in [6]. However, almost all of the above-mentioned works need a large number of samples and priori knowledge. Nevertheless, in the modern air combat, because of the confidentiality, it is not easy to obtain the battle samples. Sometimes, some information even cannot obtain efficiently, which lead to information incompleteness. In such case, the incidence analysis in grey system theory can be employed to solve this problem. Grey incidence analysis concentrates on the potential regularity of system, and has been widely used in different fields such as defensive decision-making, target recognition and target threat assessment [7]. Grey incidence analysis method is suitable for aerial target intention prediction, because it has no requirement on the size and regularity of the sample. Moreover, in the air combat, the target intention is irregular. However, the weight of traditional grey incidence analysis cannot be evaluated accurately. Hence, the fuzzy inference can be introduced to avoid this problem.

This paper is organized as follows. The air combat scenario is given and the threat factors and corresponding influence are defined in Section 2. In Section 3, the mathematical procedure of grey incidence analysis method is presented. Then, the weight is determined by fuzzy inference, which is shown in Section 4. And Section 5 presents the simulation results. The conclusion is drawn in the last section.

2. **Problem Statement and Preliminaries.** Due to the regularity of aerial target intention, different behavioral characteristics can reflect the various results. On the contrary, these behavioral characteristics can also reflect the target intention of combat. Considering all factors that influence the target intention, the angle, distance, velocity, altitude, energy and capability are defined as the prediction input variables and the maneuvers of UCAVs are also considered.

The air combat situation between UCAV I and the target J is shown in Figure 1 [8].

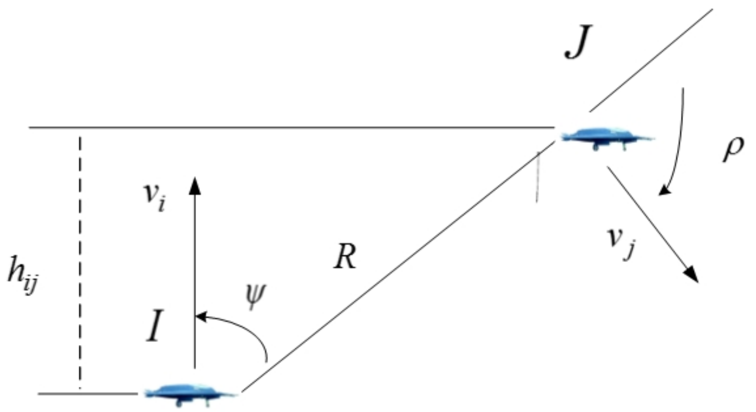

FIGURE 1. Airfight situation of two fighters

In Figure 1, we define the line between two fighters is the target line of sight; R is the distance between two fighters; ψ is the angle between the target line of sight and the direction of velocity v_i of I, called position angle; ρ is the angle between the extension of target line of sight and the direction of velocity v_j of J, called the target entrance angle. Here, two angles are positive if they are both on the right side of the target line. Therefore, there have $0 \le |\psi| \le 180°$ and $0 \le |\rho| \le 180°$. h_{ij} is the height difference, $h_{ij} = h_i - h_j$, and h_i and h_j are the height of UCAV and target. To predict the target intention, the six threat factors are defined as follows.

According to Figure 1, using the position angle and the target entrance angle, the angle threat factor t_α is defined as [8]:

$$t_\alpha = (|\psi| + |\rho|)/360° \quad (1)$$

when the position angle $\psi = 0$, which indicates the target is right in front of our UCAV. Obviously, $\rho = 0$ indicates the target is directly behind our UCAV. When $\psi = \rho = 90°$, $t_\alpha = 0.5$. Namely, two fighters are balance of power.

Using distance and some information of UCAVs, the distance threat factor t_r including two cases is defined as follows [8].

Case 1: if the target capacity is better, we have $rm < rmt < rr < rrt$. Then, we define

$$t_r = \begin{cases} 0.5, & R < rm \text{ or } rmt < R < rr \\ 0.5 + 0.2 \cdot (R - rm)/(rmt - rm), & rm < R < rmt \\ 0.5 + 0.1 \cdot (R - rr)/(rrt - rr), & rr < R < rrt \end{cases} \tag{2}$$

Case 2: if the target capacity is worse, we have $rmt < rm < rrt < rr$. Then, we define

$$t_r = \begin{cases} 0.5, & r < rmt \text{ or } rm < r < rrt \\ 0.5 - 0.2 \cdot (R - rmt/(rm - rmt), & rmt < R < rm \\ 0.5 - 0.1 \cdot (R - rrt)/(rr - rrt), & rrt < R < rr \end{cases} \tag{3}$$

where rm is the maximum missile range of our UCAV, rmt is the maximum missile range of target, rr is the maximum detection range of our UCAV radar, and rrt is the maximum detection range of target's radar. When the two fighters can attack each other or can only be detected and are both unable to attack each other, the power is balance. Namely, $t_r = 0.5$.

The velocity threat factor t_v is defined as [8]:

$$t_v = \begin{cases} 0.1, & v_j < 0.67v_i \\ -0.5 + v_j/v_i, & 0.67v_j \le v_i \le 1.5v_j \\ 1.0, & v_j > 1.5v_i \end{cases} \tag{4}$$

where v_i is UCAV velocity, and v_j is the target velocity. With the increase of the target velocity, the threat also increased. When $v_i = v_j$, $t_v = 0.5$. Namely, two fighters are balance of power.

The altitude threat factor t_h is given by [8]:

$$t_h = \begin{cases} \exp[-(h_{ij} + 1)^2/1.44], & h_{ij} < 0\text{km} \\ 0.5 - 0.08h_{ij}, & 0\text{km} \le h_{ij} \le 5\text{km} \\ 0.1, & h_{ij} > 5\text{km} \end{cases} \tag{5}$$

when $h_{ij} = 0$, the two fighters are at the same altitude, the power is balance with $t_h = 0.5$.

The energy factor t_E is defined as [8]:

$$t_E = \begin{cases} E_t/E, & E_t/E < 0.5 \\ 2^{E_t/E-2}, & 0.5 \le E_t/E \le 2 \\ 1, & E_t/E > 2 \end{cases} \tag{6}$$

where $E = h_i + {v_i}^2/g$ and $E_t = h_j + {v_j}^2/g$ are the energy of UCAV and target, and g is the local acceleration of gravity. When $E_t/E = 1$, the power is balance. Namely, $t_E = 0.5$.

Using the maximum missile range, the maximum detection range of UCAV radar and the missile number of UCAV, the capability threat factor t_c can be defined as [8]:

$$t_c = 0.5(rrt/rr)\sqrt{(llt \cdot rmt)/(ll \cdot rm)} \tag{7}$$

where llt and ll are the missile number of target and our UCAV. When the capabilities of two fighters are the same, the power is balance with $t_c = 0.5$.

From above discussion, the greater threat factor can lead to higher probability of the target under attack. In this paper, the target intention is divided into attack, reconnaissance, feint and circumvention, and the angle, distance, velocity, altitude, energy and capability are used as the variables of prediction. The influence of air combat status based on threat factors is obtained by experience and expert system, which are shown in Table 1.

Finally, the maneuver is introduced to modify the result, and the maneuvers of target are divided as hover, subduction, roll and climb. Each maneuver has different importance on different intentions. If the target is hovering, it means that the target has more possibility in reconnaissance. Moreover, subduction indicates attack or feint, roll means circumvention and climb related to attack, feint or circumvention.

Table 1. The influence of air combat status from threat factors

Intentions / *Threat Factors*	*Attack*	*Reconnaissance*	*Feint*	*Circumvention*
0-0.1	0.05	0.05	0.05	0.85
0.1-0.2	0.10	0.15	0.10	0.65
0.2-0.3	0.15	0.20	0.10	0.55
0.3-0.4	0.15	0.25	0.20	0.40
0.4-0.5	0.25	0.35	0.25	0.15
0.5-0.6	0.30	0.25	0.30	0.10
0.6-0.7	0.60	0.10	0.20	0.05
0.7-0.8	0.70	0.05	0.20	0.05
0.8-0.9	0.85	0.05	0.10	0
0.9-1.0	0.95	0	0.05	0

3. **Grey Incidence Analysis.** Grey incidence analysis is one of the most important contents of grey theory, which could expediently and rapidly extract the effective and important factors from the complex system [9], and it is especially available to deal with the incomplete information problems.

The definitions of grey incidence are as follows [10].

Select reference sequence as $u_{i_0j_0} = \left(u_{i_0j_0}^{(1)}, u_{i_0j_0}^{(2)}, \ldots, u_{i_0j_0}^{(s)}\right)$, where s means the number of targets, and i, j mean the characteristics of the sequence. The comparison sequence is $u_{ij} = \left(u_{ij}^{(1)}, u_{ij}^{(2)}, \ldots, u_{ij}^{(s)}\right)$.

If some information is missing, or cannot be obtained, we define corresponding $u_{ij} = 0$.

Then, the grey incidence grade, namely, the ith target's jth intention incidence grade is given by [10]

$$\varepsilon_{ij}^{(k)} = \frac{\min\limits_{\substack{1\le i\le n\\1\le j\le m}} \min\limits_{1\le k\le s} \left|u_{i_0j_0}^{(k)} - u_{ij}^{(k)}\right| + \kappa \max\limits_{\substack{1\le i\le n\\1\le j\le m}} \max\limits_{1\le k\le s} \left|u_{i_0j_0}^{(k)} - u_{ij}^{(k)}\right|}{\left|u_{i_0j_0}^{(k)} - u_{ij}^{(k)}\right| + \kappa \max\limits_{\substack{1\le i\le n\\1\le j\le m}} \max\limits_{1\le k\le s} \left|u_{i_0j_0}^{(k)} - u_{ij}^{(k)}\right|} \tag{8}$$

where κ $(0 < \kappa < 1)$ is the distinguishing coefficient. If κ is smaller, the greater resolution is obtained.

Considering the weights of each factor, we have $\Xi = \sum\limits_{k=1}^{s} \omega^{(k)}\varepsilon_{ij}^{(k)}$, where $\omega^{(k)}$ is weight of factor k, which means the importance of the kth threat factor. Then, the grey incidence matrix can be expressed as

$$\Xi = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & \cdots & \varepsilon_{1N} \\ \varepsilon_{21} & \varepsilon_{22} & \cdots & \varepsilon_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ \varepsilon_{M1} & \varepsilon_{M2} & \cdots & \varepsilon_{MN} \end{bmatrix} \tag{9}$$

Obviously, if ε_{ij} is greater, the target is more likely showing the corresponding intention.

4. **Fuzzy Inference of Grey Incidence Weights.** In general case, the weights of grey incidence analysis method obtained from the expert experience, which are not easy to change once are determined. Since the influence of the factor features and the environment in the practical application, the weights are often different. If we do not care about this problem, the results are not reliable. Therefore, we design a new method to avoid this problem in the following description.

Actually, there is no specific mathematical expression for computing. Thus, it is difficult to choose the weight directly. Fuzzy inference has great advantages and has already well-used to this sort of problem. We give the various factor weights of air target intention prediction based on expert experience and fuzzy inference.

Assuming that the intermediate variable $\lambda_i \in [0, 0.1, \ldots, 0.9, 1.0]$. Angle threat factor $t_\alpha \in [VS, S, M, L, VL]$, distance $R \in [LS, S, M, F, LF]$, velocity threat factor $t_v \in [VS, S, M, L, VL]$, altitude $H \in [NF, NM, NS, Z, PS, PM, PF]$, energy threat factor $t_E \in [VS, S, M, L, VL]$ and capability threat factor $t_c \in [VS, S, M, L, VL]$. $VS \sim VL$ means the threat factor from small to large. $LS \sim LF$ means the distance between target and our UCAV from near to far. $NF \sim PF$ is the range of altitude intercept from negative far to positive far between target and our UCAV. Figure 2 to Figure 7 are the membership function curves of t_α, R, t_v, H, t_E and t_c. On the basis of the airfight status and according to the size of t_α, R, t_v, H, t_E and t_c, in accordance with the following Table 2 to Table 7 to determine λ_i.

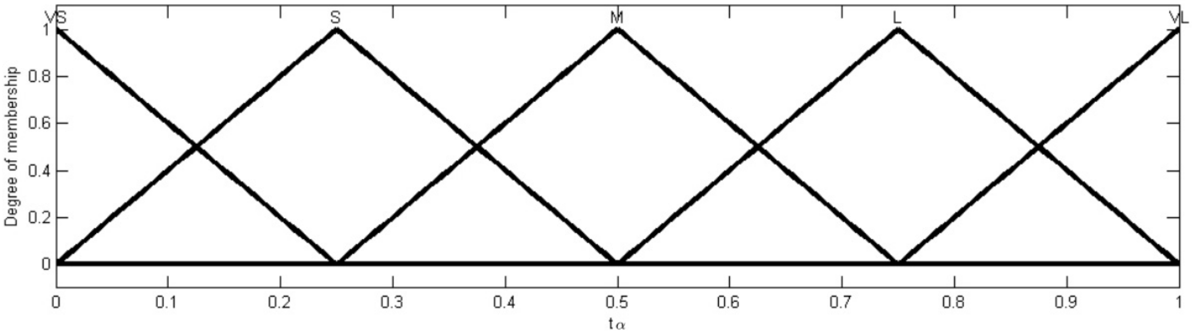

FIGURE 2. Membership function curve of t_α

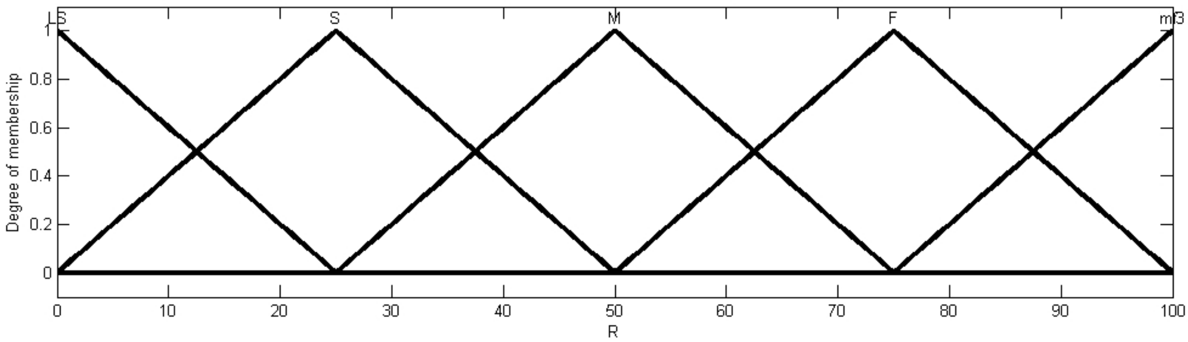

FIGURE 3. Membership function curve of R

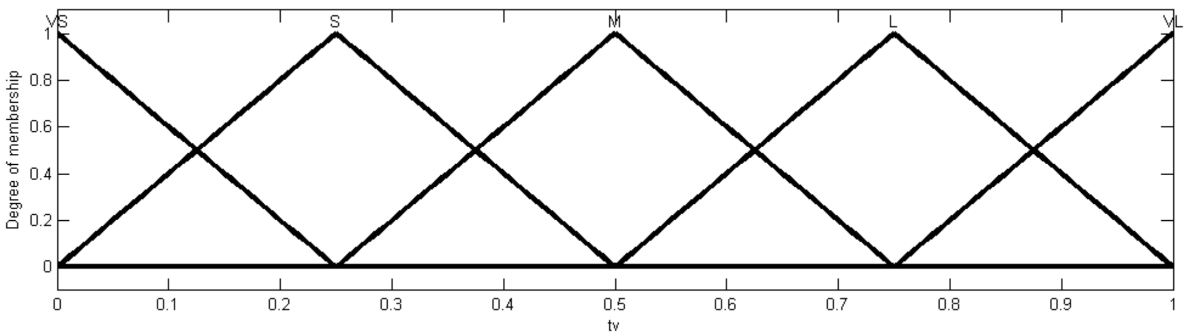

FIGURE 4. Membership function curve of t_v

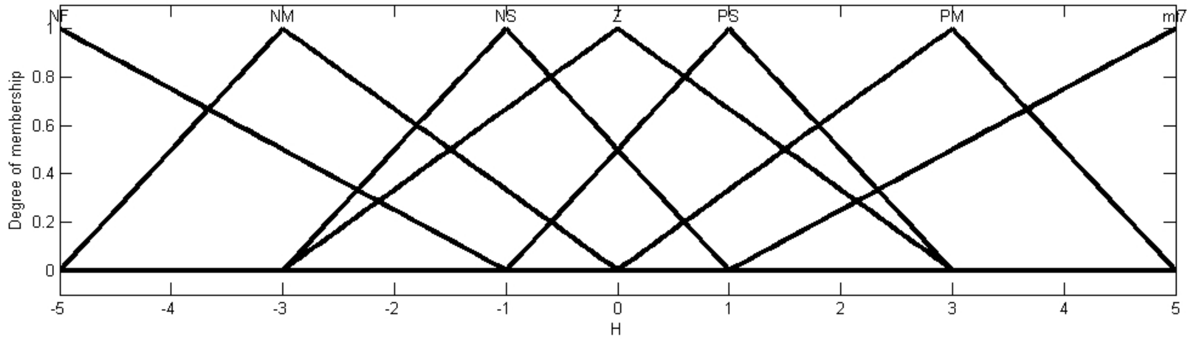

Figure 5. Membership function curve of H

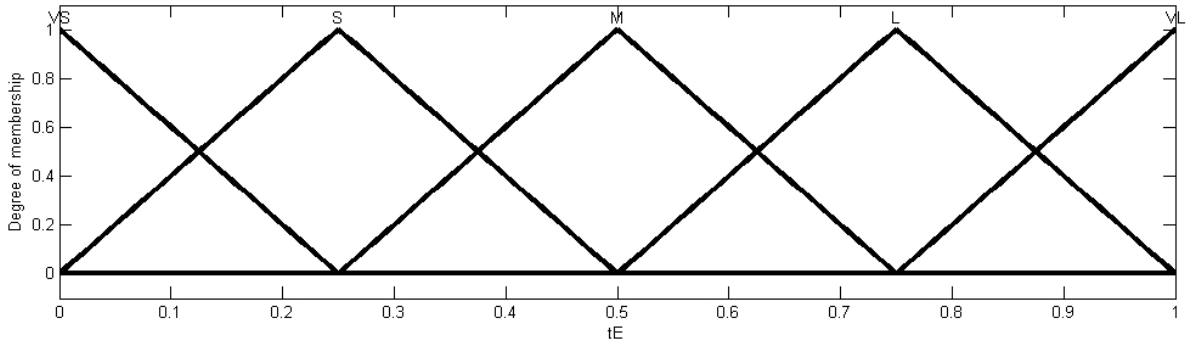

Figure 6. Membership function curve of t_E

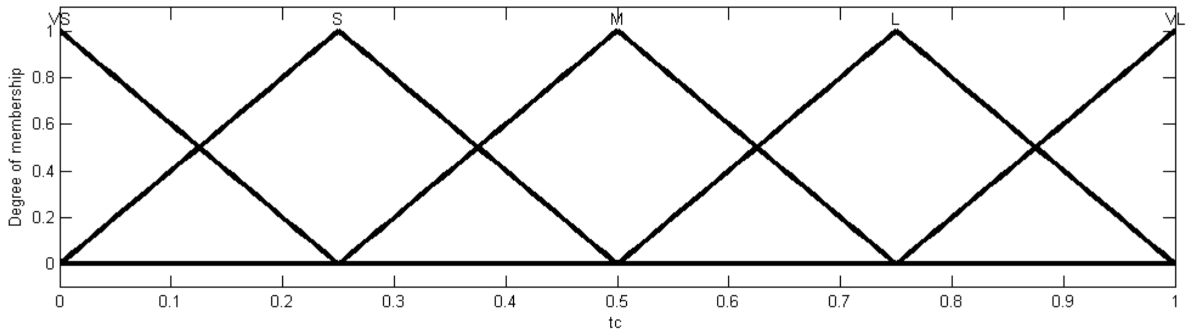

Figure 7. Membership function curve of t_c

Table 2. Fuzzy rule of λ_1

Angle t_α	VL	L	M	S	VS
λ_1	0.9	0.7	0.5	0.3	0.1

Table 3. Fuzzy rule of λ_2

Distance R	LS	S	M	F	LF
λ_2	0.9	0.8	0.5	0.2	0

If some information is missing, or cannot be obtained, we define corresponding $\lambda_i = 0$.

Table 4. Fuzzy rule of λ_3

Velocity t_v	VL	L	M	S	VS
λ_3	0.9	0.7	0.5	0.3	0.1

Table 5. Fuzzy rule of λ_4

Altitude H	NF	NM	NS	Z
λ_4	0.1	0.3	0.8	0.7
Altitude H	PS	PM	PF	
λ_4	0.5	0.2	0	

Table 6. Fuzzy rule of λ_5

Energy t_E	VL	L	M	S	VS
λ_5	0.9	0.7	0.5	0.3	0.1

Table 7. Fuzzy rule of λ_6

Capability t_c	VL	L	M	S	VS
λ_6	0.9	0.7	0.5	0.3	0.1

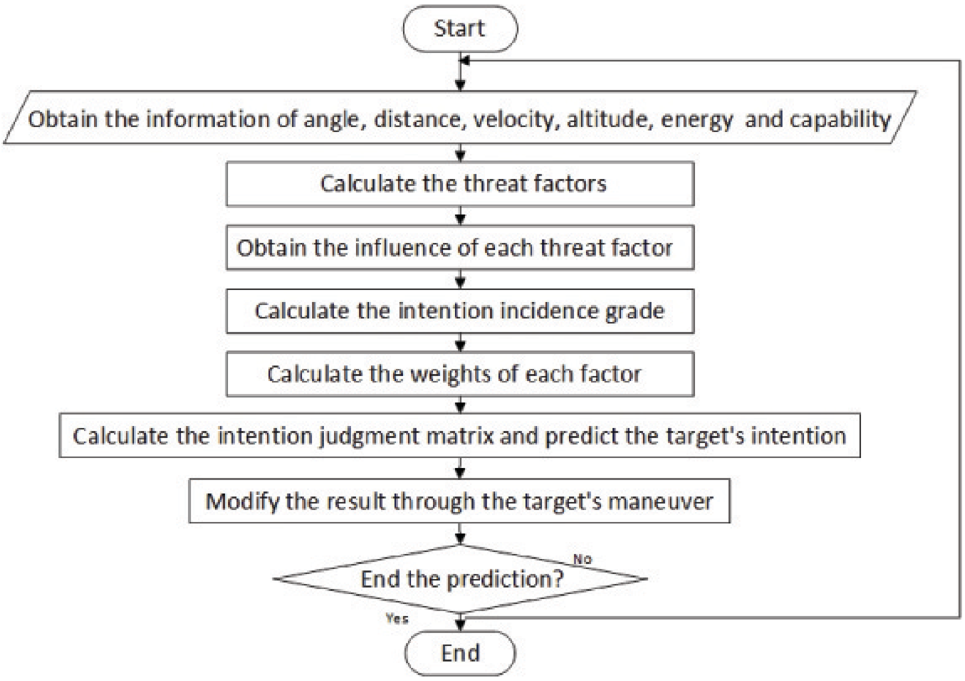

Figure 8. The flow diagram of air target intention prediction algorithm

Considering the constraint of grey incidence $\sum_{i=1}^{n} w_i = 1$, we obtain the respective weight of each factor as $\omega_i = \lambda_i \Big/ \sum_{s=1}^{n} \lambda_s$.

From above discussion, the flow diagram of air target intention prediction algorithm is shown in Figure 8.

5. **Simulation Results.** In order to verify the correctness and reliability of the above developed method, the simulation results are given. Assume that the maximum missile

TABLE 8. Initial data of airfight status

	ψ (°)	ρ (°)	R (km)	v_i (m/s)	v_j (m/s)	h_{ij} (km)
Target 1	−75	160	35.8	250.0	340.0	−1.5
Target 2	−45	45	56.7	330.0	270.0	3.0
Target 3	−75	160	∗	250.0	340.0	−1.5
	rmt (km)	rrt (km)	llt (ea)	E_t/E	*maneuver*	
Target 1	70	140	4	1.736	*subduction*	
Target 2	50	100	2	0.605	*roll*	
Target 3	70	140	4	1.736	*subduction*	

TABLE 9. Threat degree of target

	Angle	*Distance*	*Velocity*	*Altitude*	*Energy*	*Capability*
Target 1	0.6528	0.5000	0.9583	0.8406	0.8328	0.7275
Target 2	0.2500	0.2015	0.3182	0.2600	0.3802	0.3106
Target 3	0.6528	∗	0.9583	0.8406	0.8328	0.7275

TABLE 10. Intention judgment matrix of target

		Attack	*Reconnaissance*	*Feint*	*Circumvention*
Target 1	*Method* 1	0.8726	0.3827	0.4265	0.3726
	Method 2	0.8140	0.3926	0.4351	0.3764
	Method 3	0.8645	0.3857	0.4265	0.3735
Target 2	*Method* 1	0.6924	0.7343	0.6920	0.9790
	Method 2	0.6923	0.7350	0.6933	0.9750
	Method 3	0.6923	0.7395	0.7013	0.9525
Target 3	*Method* 1	0.8921	0.3788	0.4238	0.3712
	Method 2	0.7989	0.3774	0.4191	0.3709
	Method 3	0.8555	0.3765	0.4169	0.3701

range $rm = 60$km, the maximum detection range of UCAV's radar $rr = 120$km, the missile number $ll = 3$ and the test data of airfight status are shown in Table 8.

In Table 8, ∗ means the information is missing or cannot be obtained.

According to the definition of threat factors and the influence of airfight status from threat factors, the threat degrees of target 1, target 2 and target 3 are calculated, which are shown in Table 9.

Choosing the reference sequence of number as $u_{i_0j_0} = \left(u_{i_0j_0}^{(1)}, u_{i_0j_0}^{(2)}, u_{i_0j_0}^{(3)}, u_{i_0j_0}^{(4)}, u_{i_0j_0}^{(5)}, u_{i_0j_0}^{(6)}\right) = (1, 1, 1, 1, 1, 1)$.

According to (7), and choosing distinguishing coefficient $\kappa = 0.5$, we can obtain the grey incidence matrix.

Use the method based on fuzzy inference to compare with the traditional grey incidence method that sets the weight artificially. Method 1 is the method based on fuzzy inference, and the weights of method 2 and method 3 are chosen as $\omega_2^{(k)} = [1/6\ 1/6\ 1/6\ 1/6\ 1/6\ 1/6]$ and $\omega_3^{(k)} = [0.05\ 0.1\ 0.2\ 0.175\ 0.2\ 0.225\ 0.25]$, respectively. Due to the influence of the target maneuver, the corresponding intention multiplies the modified coefficient.

The intention judgment matrices of target 1, target 2 and target 3 are shown in Table 10.

Table 10 shows that the intention of target 1 is attack, the intention of target 2 is circumvention and the intention of target 3 under the incomplete information situation also is attack. The results are similar with expert experience.

From the simulation results we can find that the weight has great importance on the results of grey incidence analysis method. Compared with method 2 and method 3, the developed method is more reliable and more accurate. Thus, the method based on fuzzy inference is better than the traditional grey incidence method. When considering the incomplete information condition, this method is also reliable. The results show that the new method is effective in air target intention prediction of the incomplete information condition.

6. **Conclusion.** The target intention prediction in advance and the help for the autonomous defense decision-making of UCAVs in the incomplete information condition are paid more attention recently. In this paper, a method based on grey incidence analysis method is introduced and the weights are determined by fuzzy inference. The simulation results have showed that the method can predict the target intention effectively. It lays a foundation for future air combat decision.

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