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Research Article

A Target Damage Effectiveness Assessment Mathematical Calculation Method with Uncertain Information Based on an Adaptive Fuzzy Neural Network

Hanshan Li and Xiaoqian Zhang

School of Electronic and Information Engineering, Xi'an Technological University, Xi'an 710021, China

Correspondence should be addressed to Hanshan Li; lihanshan269@163.com

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Aiming to address the issue of assessing the effectiveness of target damage in air defense interception under projectile and target intersection, this paper proposes a novel target damage effectiveness assessment mathematical calculation method using an adaptive fuzzy neural network. The design and calculation methods introduce the target cabin's damage weight factor, the dispersion error and coverage density and fire density of warhead fragment, and the ratio of the number of warhead fragments to the cross-sectional area of the target as the primary damage factors, and we establish a new model for calculating the target damage efficiency using Takagi-Sugeno adaptive fuzzy neural network with the multiple damage factors. In the designed model, we take the characteristic parameters of warhead fragments formed by the projectile explosion as the sample data and learn the mapping relationship between damage factors and damage effect expressed by the system of fuzzy rule. Combined with the vulnerability weight and damage factors of the target, the fuzzy rule system is applied to predict and calculate the damage probability and damage effectiveness. In addition, we use shot-line technology to set up the intersection criterion between warhead fragments and target, analyze the coordinate relationship of the projectile explosion relative to the target based on the ground coordinate system, and derive the distribution density function of warhead fragment and research a calculation model for target damage probability with multiple vulnerable cabins. Finally, we use the established model to train, test, and calculate the data from the actual projectile and target intersection damage test and present the comparison results to other damage calculation methods. By calculation and comparative analysis, the results show the smaller the distance between projectile and target, as well as the smaller the average intersection angle, and the larger the weight coefficient of the warhead fragment covering the target cabin, the total target damage probability increases obviously. In the two experimental calculations, the target cabin with the largest weight coefficient was considered, and compared with the existing literature, the damage probability of the proposed calculation method was increased by 9.13% and 10.93%, respectively, and it is clear that the proposed target damage assessment method can effectively reflect the real target damage effectiveness in the state of projectile and target intersection.

1. Introduction

1.1. Problem Statement. Theoretical and methodological research on target damage testing and assessment has always been a research hotspot and difficult problem in weapon development and performance test methods. Due to the large number of damage factors involved in evaluating and calculating target damage effectiveness, it is difficult to quantify the damage factors. Additionally, the damage evaluation parameters required for the actual test are difficult to obtain, resulting in the absence of scientific evaluation calculation methods for determining the effectiveness of target damage [1, 2]. Particularly, in the target damage effectiveness evaluation of a space air defense intercept under projectile and missile target space intersection, because it is extremely difficult to obtain more accurate damage data to evaluate the target damage result, this kind of target damage is related to the parameters, such as the relative position of projectile explosion, the distribution density and hit probability of warhead fragment, and the target's multiple vulnerability characteristics. These damage parameters are mathematically expressed as uncertain, incomplete, or fuzzy, which is the main problem of target damage effectiveness evaluation of a space air defense intercept at present.

In addition, the target's vulnerability law is also uncertain, making it more difficult to develop a scientific theoretical model and evaluation system for evaluating the target damage effectiveness that is caused by air defense projectile proximity explosions [3, 4]. It is primarily manifested in three ways:

(1) The random uncertainty in the dispersion of warhead fragments
(2) The uncertain situation distribution of the warhead fragments' power field
(3) The uncertainty in damage parameters such as the vulnerable damage factor, damaging weight, and damage grade of the target.

These uncertain factors create a fuzzy logical relationship, making it difficult to quantify the damage effectiveness of the target with intuitive fixed functions.

The traditional test and calculation of target damage only consider the test method of the target itself, while ignoring the scientific calculation problem between the spread power situations of the warhead fragment group. As a result, repeated tests in the actual test cost a lot of money, material resources, and manpower and cannot produce the ideal effect. Given the ongoing expansion of the air combat situation in the current international situation, evaluating the target damage effectiveness of a space air defense intercept remains a hot research topic and an unsolved scientific problem. To improve the air defense combat ability, it is necessary to investigate the method of target damage evaluation under uncertain information parameters between projectile and target space intersection.

1.2. State-of-the-Art Review. Currently, there are few research methods for assessing target damage with uncertain information. Most existing studies use known and determined information data to evaluate the effect of target damage. These evaluation methods are divorced from the actual state of the damaged missile attacked by the warhead fragment group. For example, in [5], Wadagbalkar and Liu researched a comprehensive performance analysis system and developed an effective tool for real-time prediction of projectile penetrations to laminates. In [6], Tian et al. investigated the effect of proximity fuze on ammunition damage assessment using the fuze real-time explosion point statistical model. This model only considers the blast position of the projectile fuze and does not describe the relationship between the attacking angle and velocity of the projectile and the damaged factor of target. The actual damage is subject to many constraints, such as the vulnerable parts of the target, the characteristics of target materials, and the spread of the warhead fragment group caused by the projectile explosion, among others. If only the fuze real-time explosion point parameters are considered, the target damage cannot be accurately determined. Additionally, Si et al. established a model for assessing the damage of fragmentation warheads against airplane targets. By analyzing the relationship between component damage and airplane damage, the airplane's damage probability was calculated from component damage. The model can be used to evaluate the damage capability of the fragmentation warhead against airplanes under any conditions of warhead fragment and target encounter. However, this damage model must be established on the basis that the distribution of damaged parts of the target is known, and the damage condition must be modified to calculate the damaging effect of the fuzzy and uncertain target [7]. The authors of [8] proposed an algorithm for evaluating airport target damage based on visible light images assuming that the wartime airport meets the minimum combat conditions, the camera technology captures the target images and can be intuitive to see images of the target damage, and it is a relatively straightforward method for calculating and evaluating damages to target. However, because the state of confrontation between an incoming projectile and a space target is somewhat random, it is very difficult to gain an intuitive and clear image of a damaged target. In reference [9], Wu and Zhao presented a novel model for predicting the damaging effect of artillery firing on group targets using an adaptive neuro-fuzzy inference system (ANFIS). Additionally, Wang et al. proposed a calculation model that obtains all hitting point parameters by only numerating fragments once and analyzing the target's damage probability through simulation [10]. Aiming at solving difficulties of lacking coherent and complete analysis on the effectiveness of hitting and terminal damage for armored targets, in [11], Han and Huang combined the characteristics of armored targets to carry out the evaluation and analysis of the damage effectiveness of different firepower equipment striking schemes. Additionally, Lu et al. constructed a calculation model for calculating the damage probability to an air target caused by a distributed MEFP warhead using shot-line technology, and the change law of missile damage probability caused by warhead fragment attack is calculated using Monte-Carlo simulation [12].

In addition, some researchers have investigated various evaluation methods of target damage in various fields and proposed many novel ideas. Zhang et al. proposed a damage test method on typical fragments destroy concrete targets, analyzed the dimensionless relationship between depth of invasion and influencing factors, and carried out the scaled model of the equivalent design of the concrete targets and used the sand-removal method to accurately obtain damage parameters [13]. In order to solve the disadvantages of the degraded states vulnerability methodology in target damage assessment, which cannot reason bidirectionally, nor can it describe the dynamic damage status, Xu et al. proposed the degraded states vulnerability methodology based on T-S dynamic damage tree and Bayesian network [14]. Moon provides a review of methods for determining the effectiveness of a fragmentation weapon against a point target or an area target, emphasizing the need to use the Carleton damage function with the correct shape factor [15]. Deng et al. developed a cloudy Bayesian network-based early warning radar damage evaluation model by combining a Bayesian network and a cloud model to create a cloudy Bayesian network and convert the cloud model for various indicator system variables [16]. For the deficiencies of the traditional expert experience method in deriving the conditional probability, the dempster-shafter/analytic hierarchy process is used to determine the conditional probability value of each node. The variables are input into the cloudy Bayesian network, and the damage probability that the early warning radar belongs to each damage level is inferred; this method plays a significant role in radar damage assessment.

All of these references have described the damage probability calculation method based on specific known damage parameters in various fields; however, there has been relatively little research on the calculation and evaluation of damage caused by the collision of projectile and target (missile) while in the air. The effect of this damage is crucial for evaluating the precise attack and damage of projectile fuze on air targets. It is also a pressing scientific issue that must be resolved immediately.

1.3. Research Gap and Motivation. When the projectile and the incoming target (missile) meet, there is a certain resistance between them, which makes the projectile control fuze initiation time delay, resulting in a random distribution of the projectile explosion; so, it more difficult to evaluate the damaging effect of the incoming target. All of these show that many uncertain factors affect the evaluation of target damage, and it is necessary to transform the fuzziness of multiple uncertain factors into a deterministic theoretical model for calculation and analysis. Certainly, some recent publications have proposed methods for calculating damage to a target using uncertain and fuzzy information. Wei and Li used fuzzy reasoning to set up a comprehensive damage evaluation model, which accounted for the complexity of target damage effect evaluation [17]. Du et al. researched a Bayesian network parameter learning algorithm for target damage assessment and discussed the expectation maximization algorithm based on expert experience [18]. However, this algorithm requires a large number of known empirical data to calculate the target damage. For some uncertain damage information data, there are significant differences when using the Bayesian network parameter learning algorithm to determine the target damage assessment. Catovic and Kljuno developed a novel method for determining the lethal radius of high-explosive artillery projectiles to obtain target damage data [19]. In a real-world test scenario, the accurate damage information and evaluation parameters are hard to get through precise testing. Little research has been conducted on evaluating the effectiveness of target damage, particularly on the dynamic characteristics of random warhead fragments and target information in an uncertain environment.

According to the damage calculation and evaluation methods reported in the existing literature, most of them focus on the core parameters such as the known warhead fragment distribution and target vulnerability but ignore the uncertain fragment distribution generated by the random location of the projectile explosion and the influence of different target self-damage factors. As a result, there is a large gap between the evaluation theory of existing literature and the target damage results of actual experiments.

The research motivation of this paper is aimed at the target damage caused by the warhead fragments produced by the uncertain projectile explosion, and this is the focus and difficulty of space target damage assessment. For scientific and reasonable evaluation of target damage efficiency, we have also done a lot of research on the damage of fragments penetrating the target. For example, in [20], to scientifically evaluate the target damage effect when the projectile attacks the aircraft target, we introduce a game confrontation mechanism and set up an aircraft target damage game strategy model. In [21, 22], we measured the actual position of warhead fragment dispersion through the method of multiscreen sensors intersection test system and, based on the basis of mastering the fragment dispersion mechanism, studied the damage probability calculation of equivalent target that caused by warhead fragment dispersion. In [23], we treated the projectile and the incoming target as players in a two-person zero-sum game when the projectile and target (missile) intersected, established the profit-loss value of the warhead fragment, and discussed and calculated the effect of target damage under in a known counter parameter. These studies mainly involve relatively clear damage factors, but there are many uncertain parameters for the target damage at the intersection of the projectile target, and the existing calculation model needs to be improved.

1.4. Contribution and Overall Objective of the Study. This paper proposes a novel method for assessing target damage based on an adaptive fuzzy neural network system. To be able to apply the adaptive fuzzy neural network model intuitively, we divide the target into multiple compartments based on the spatial relationship between the projectile explosion position and the target and on the target's vulnerable characteristics. Taking into account the dispersion error and coverage density and fire density of the warhead fragment, and the target cabin's damage weight factor, our research objective is to develop a new mathematical model for assessing the effectiveness of target damage using an adaptive fuzzy neural network system and demonstrate the calculation method, which can give the target damage results closer to the actual test.

The primary contributions and innovations of this paper are as follows:

(1) To master the target damage effectiveness, we research and set up the spatial coordinate relationship between the projectile and the target, as well as the dispersion characteristics of warhead fragments when the projectile explodes. In addition, we obtain the conversion relationship calculation function between spatial geometric data in the ground

coordinate system and the explosion point coordinate system.

(2) To scientifically determine the damage degree caused by the uncertain warhead fragment group to the target and determine the position information of the warhead fragment group created by the projectile explosion to penetrate the target, we divide the target into finite cubes and set up the criterion using shooting line technology. Additionally, according to the prerequisite of warhead fragments striking the target, we developed a new model for calculating the probability of target damage based on the number and the dispersion error of warhead fragments striking the target.

(3) According to the electronic guidance, explosive fuel, and other vulnerable parts of the missile, the damage weight factor of the target cabin is introduced. The main damage factors are the dispersion error of the warhead fragment striking the target, warhead fragment coverage density, and warhead fragment fire density as the main damage factors. We propose a damage efficiency assessment calculation method by using an adaptive fuzzy neural network with damage factors as input variables and set up the damage assessment model with an adaptive fuzzy neural network, giving the calculation steps and methods of target damage assessment.

(4) Based on the position where the projectile exploded relative to the missile and the quantitative prefabricated fragments that attack the missile at different intersection angles, we use the damage assessment model with an adaptive fuzzy neural network to train, test, and calculate the data from the actual projectile-target intersection damage test. The results indicate that the proposed model and method can effectively map the real damage effectiveness.

The remainder of this paper is organized as follows: Section 2 states a design principle of target damage effectiveness assessment based on an adaptive fuzzy neural network. Section 3 states the spatial coordinate relationship between the projectile and target in the damage test. Section 4 establishes the intersection criterion for the warhead fragment and target. Section 5 investigates the mathematical method for calculating the target damage probability. Section 6 establishes the target damage efficiency evaluation and numerical calculation using an adaptive fuzzy neural network. The validation method and calculation result are provided in Section 7. Finally, Section 8 concludes this paper and gives future work.

2. A Design Principle of Target Damage Effectiveness Assessment Based on an Adaptive Fuzzy Neural Network

Aiming at the target damage assessment of air defense interception under projectile and target intersection, the target damage effectiveness involves many factors, such as projectile flight velocity, target flight velocity, the spatial coordinate of the projectile explosion, and warhead fragment dispersion parameters. Among them, the warhead fragment dispersion parameters are related to the mean square error, density, and fire density. There is uncertainty about these factors. In order to evaluate the target damage effectiveness of air defense interception scientifically, we introduce an adaptive neural network to establish a new model for calculating the target damage efficiency. Figure 1 gives a design principle and procedure for target damage effectiveness assessment based on an adaptive fuzzy neural network.

This paper uses the Takagi-Sugeno basic model as an adaptive fuzzy neural network core logic operation, takes the characteristic parameters of warhead fragments formed by the projectile explosion as the sample data, and learns the mapping relationship between damage factors and damage effect expressed by the system of mold fuzzy rule. Combined with the vulnerability weight and damage factors of the target, the fuzzy rule system is applied to predict and calculate the damage probability and damage effectiveness. The specific design procedure is as follows.

First, according to the intersection of the distance between projectile and target, determine the projectile explosion position, and set up intersection criterion and spatial coordinate relation between warhead fragments and target, form the judgment condition that the warhead fragment attacks the target. Through the projectile explosion position and projectile flight attitude, we quantitatively calculate and analyze the distribution characteristics of warhead fragment groups and solve their parameters, including the mean square error, density, and fire density of warhead fragment groups.

Second, we introduce the damage vulnerability weight and damage factor of the target to establish the target damage probability calculation function. By dividing the target into finite cabins, the damage probability of each cabin under an effective warhead fragment attack is solved by using the vulnerability weight and damage factor of the cabin.

Third, according to the distribution of warhead fragments and the Takagi-Sugeno adaptive fuzzy neural network model, we define the damage factor set, such as the distance deviation of the warhead fragment group, the density of warhead fragments covering the cabin, the warhead fragment fire density hitting cabin, and the ratio between the coverage area of warhead fragments and target. These parameters can be used as input variables of the adaptive fuzzy neural network, and we use the algorithm of the target damage efficiency assessment model with an adaptive fuzzy neural network to calculate the target damage result.

3. Spatial Relationship between Projectile and Target in Damage Test

The target damage effect mainly focuses on the spatial coordinate relationship between the projectile explosion and the target in space intersection. The warhead fragment formed by the projectile explosion has a certain divergence

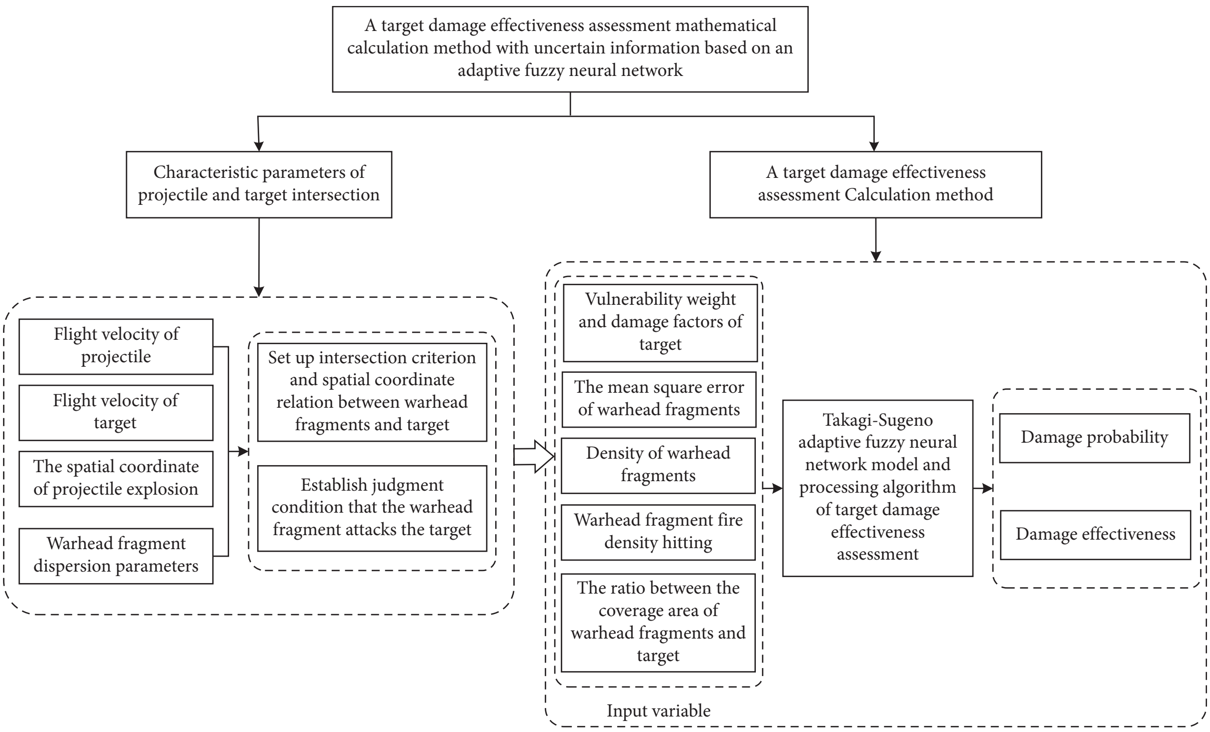


Figure 1: A design principle and procedure of target damage effectiveness assessment based on an adaptive fuzzy neural network.

angle, as shown in Figure 2. Point A is the center of the mass of the projectile, and AB is the projectile flight center axis. ϕ_1 and ϕ_2 are the static minimum and maximum flying directions angle of warhead fragments and AB, ϕ_0 is the scattering angle of the warhead fragment and AB, and $\Delta\phi$ is the static flying angle of the warhead fragment and AB.

When the target's end velocity is superimposed, the dynamic interval angle between the warhead fragment and the projectile flight center axis is calculated using the following formula:

$$\begin{cases} \phi_{\min} = \arctan\left(\dfrac{v_0 \sin \phi_1}{v_0 \cos \phi_1 + v_d}\right), \\ \\ \phi_{\max} = \arctan\left(\dfrac{v_0 \sin \phi_2}{v_0 \cos \phi_2 + v_d}\right). \end{cases} \quad (1)$$

In (1), v_0 is the static initial velocity, and v_d is the terminal velocity of the target when the projectile encounters the target in space, $0 \le \phi_{\max} \le \phi_2$. The velocity of the warhead fragments can be expressed by the following formula:

$$v = \sqrt{{v_0}^2 + {v_d}^2 + v_0 v_d \cos \phi}, \quad (2)$$

where ϕ is the scattering angle between the flight direction of warhead fragment and the motion direction of target.

To assess the target damage effectiveness when the projectile attacks the target, Figure 3 illustrates the intersection principle and the spatial coordinate relation. To conduct an objective analysis of the damage caused by warhead fragments to the target, the damage test system must establish a coordinated relationship between the ground, projectile explosion, and target.

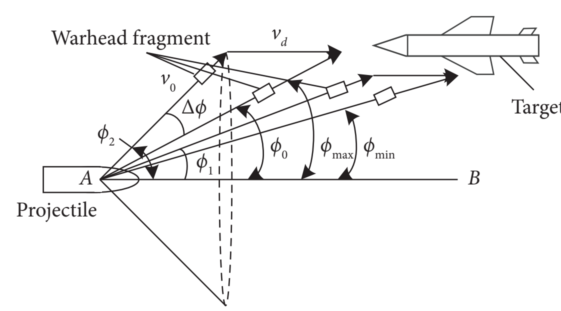


Figure 2: Schematic diagram of warhead fragment divergence.

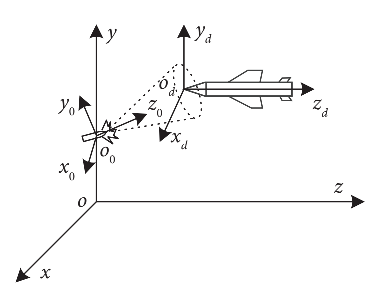


Figure 3: The intersection principle and the spatial coordinate relation on projectile and target.

Assuming that the ground coordinates system is defined as $oxyz$, the projectile explosion coordinates system is defined as $o_0x_0y_0z_0$, and the target coordinates system is defined as $o_d x_d y_d z_d$. The explosion center of the projectile is set on the oy axis of the ground coordinate system; that is, o_0 is on the oy axis, and $oo_0 = h$; usually, the center of mass of projectile A is regarded as the origin of the projectile explosion coordinates system.

In the coordinate system $oxyz$, set Q_1 as the transformation matrix between the coordinate system $o_d x_d y_d z_d$ and the coordinate system $oxyz$ [24], it can be obtained by the following formula:

$$Q_1 = \begin{bmatrix} A_1 & B_1 & C_1 \\ A_2 & B_2 & C_2 \\ A_3 & B_3 & C_3 \end{bmatrix}, \tag{3}$$

where (A_i, B_i, C_i) are the direction cosine values of the target coordinate axis in the coordinate system $oxyz$, $i = 1, 2, 3$. Then, the coordinate values (x, y, z) of any point (x_d', y_d', z_d') of the target coordinate system in the coordinate system $oxyz$ can be expressed by the following formula:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = Q_1^{-1} \cdot \begin{bmatrix} x_d' \\ y_d' \\ z_d' \end{bmatrix} + \begin{bmatrix} x_d \\ y_d \\ z_d \end{bmatrix}. \tag{4}$$

Assuming that the warhead fragment has a mass center that coincides with the projectile explosion point o_0, its coordinate value in the coordinate system of $oxyz$ is $(x_{o_0}, y_{o_0}, z_{o_0})$. If the velocity of the warhead fragment in the coordinate system $oxyz$ at the moment of projectile explosion is (v_{0x}, v_{0y}, v_{0z}), from the projectile explosion coordinate system $o_0 x_0 y_0 z_0$, the azimuth and pitch angles of the warhead fragment can be calculated using the following formula:

$$\begin{cases} \alpha = \arctan \dfrac{v_{0x}}{v_{0z}}, \\ \beta = \arctan \dfrac{\sqrt{v_{0x}^2 + v_{0z}^2}}{v_{0y}}, \end{cases} \tag{5}$$

where α and β are the azimuth and pitch angles of the warhead fragments, respectively. Then, the conversion matrix from the coordinate system $oxyz$ to the projectile explosion coordinate system of $o_0 x_0 y_0 z_0$ is shown in the following formula:

$$Q_2 = \begin{bmatrix} \cos\alpha \cdot \cos\beta & \sin\alpha \cdot \cos\beta & -\sin\beta \\ -\sin\alpha & \cos\alpha & 0 \\ \sin\beta \cdot \cos\alpha & \sin\alpha \cdot \sin\beta & \cos\beta \end{bmatrix}. \tag{6}$$

As a result, formula (7) illustrates the conversion relationship between spatial geometric data in the ground coordinate system and the explosion point coordinate system.

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = Q_2 \cdot \begin{bmatrix} x - x_{o_0} \\ y - y_{o_0} \\ z - z_{o_0} \end{bmatrix} = \begin{bmatrix} \cos\alpha \cdot \cos\beta & \sin\alpha \cdot \cos\beta & -\sin\beta \\ -\sin\alpha & \cos\alpha & 0 \\ \sin\beta \cdot \cos\alpha & \sin\alpha \cdot \sin\beta & \cos\beta \end{bmatrix} \cdot \begin{bmatrix} x - x_{o_0} \\ y - y_{o_0} \\ z - z_{o_0} \end{bmatrix}. \tag{7}$$

4. The Intersection Criterion on Warhead Fragments and Target

Take the ground coordinate system as the reference system, it is assumed that the warhead fragment starts to fly outward at any point (x_0, y_0, z_0), and its velocity vector is (v_{0x}, v_{0y}, v_{0z}). When the target is relatively stationary, then the linear equation of warhead fragment flight trajectory after the time of Δt, the projectile explosion coordinate can be gained by formula (8) in the coordinate system of $oxyz$.

$$\begin{cases} x = x_0 + (v_{0x} - v_{\Delta tx}) \cdot \Delta t, \\ y = y_0 + (v_{0y} - v_{\Delta ty}) \cdot \Delta t, \\ z = z_0 + (v_{0z} - v_{\Delta tz}) \cdot \Delta t, \end{cases} \tag{8}$$

where $(v_{\Delta tx}, v_{\Delta ty}, v_{\Delta tz})$ is the flying velocity of the warhead fragment after the time of Δt.

To scientifically determine the damage degree caused by the warhead fragment group to the target, it is necessary to determine the position information of the warhead fragment group on the target's surface. We divide the target into finite cubes, suppose that the four angular coordinates of any element cube are $a_1(x_{a_1}, y_{a_1}, z_{a_1})$, $a_2(x_{a_2}, y_{a_2}, z_{a_2})$, $a_3(x_{a_3}, y_{a_3}, z_{a_3})$, $a_4(x_{a_4}, y_{a_4}, z_{a_4})$, as shown in Figure 4.

Any three points can determine the normal $\overline{N}(A, B, C)$ of the plane containing the target unit. When formula (9) is satisfied, the straight trajectory line of the warhead fragment intersects the plane $a_1 a_2 a_3 a_4$ of the target unit, and the warhead fragment may cause damage to the target.

$$A(v_{0x} - v_{\Delta tx}) + B(v_{0y} - v_{\Delta ty}) + C(v_{0z} - v_{\Delta tz}) \neq 0. \tag{9}$$

If formula (9) is not satisfied, there is no intersection between the warhead fragment and the target in the unit plane $a_1 a_2 a_3 a_4$, and the warhead fragment does not damage the target. Simultaneously, various triangular facets are formed using the target surface's four angular coordinates, and the triangular area method is used to determine whether the midpoint belongs to the target facet. This method is used to determine whether the sum of the areas of any two vertices of a point and a triangle equals the triangle's area [25–27]. The intersection point is in the triangle if the sum of the areas of any two vertices of a point and a triangle equals the area of the triangle. Otherwise, it is not contained within the triangle. Take the triangle $\Delta a_1 a_2 a_3$ formed by points

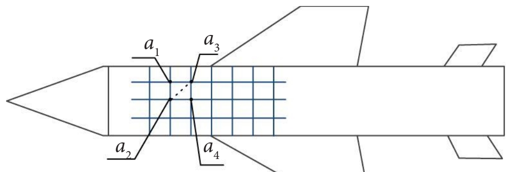


FIGURE 4: A diagram of a target dividing itself into a finite number of cubes.

$a_1(x_{a_1}, y_{a_1}, z_{a_1})$, $a_2(x_{a_2}, y_{a_2}, z_{a_2})$, and $a_3(x_{a_3}, y_{a_3}, z_{a_3})$ as an example, point M is the judgment point, and the judgment condition is decided by the following formula:

$$S(\Delta M a_1 a_2) + S(\Delta M a_2 a_3) + S(\Delta M a_1 a_3) \geq S(\Delta a_1 a_2 a_3). \tag{10}$$

If the equal sign is used in the preceding formula, the M point is located in the triangular bin; that is, the warhead fragment hits the triangle $\Delta a_1 a_2 a_3$ of the target surface. The M point's coordinates are the warhead fragment's hit point parameter. Otherwise, the M point is located outside the target surface's triangular bin; the warhead fragment thus misses the target bin.

5. Mathematical Calculation Method of Target Damage Probability

According to the fragmentation dispersion characteristics, the straight line of the warhead fragment track intersects the plane of the damaged target unit, indicating that the warhead fragment is likely to cause target damage. To simplify the calculation of the target's damage probability, we consider only the warhead fragments' dispersion within the target coordinate system. The coordinates of warhead fragments in the target are calculated using the space conversion relationship among the ground, the projectile explosion position, and the target. The target coordinate system $o_d x_d y_d z_d$ is the relative coordinate system of the intersection of warhead fragments. The target surface is regarded as the sum of the multiple-unit square plane $a_1 a_2 a_3 a_4$. According to the judgment conditions of formula (10), whether warhead fragments effectively attack the area of the unit square plane $a_1 a_2 a_3 a_4$ is determined as the prerequisite for damage. The target has multiple different key cabins. We divide the target into N cabins and define j as the serial number of the cabin, that is, $j = 1, 2, \cdots, N$. The damage probability of each cabin can be equivalent to the damage probability that warhead fragments hitting the cabin effectively in the $x_d o_d y_d$ and $y_d o_d z_d$ coordinate planes, and the N cabins are independent of each other.

In the j-th cabin, assuming that the coordinates of any warhead fragment in the coordinate system $o_d x_d y_d z_d$ be (x_d, y_d, z_d). We use the formula (11) to establish the distribution density function of the warhead fragment in the two directions of the plane $x_d o_d y_d$ and $y_d o_d z_d$.

$$f(x_d, y_d, z_d) = \begin{cases} \dfrac{1}{2\pi\sigma_{x_d}\sigma_{y_d}} \exp\left(-\dfrac{x_d{}^2}{2\sigma_{x_d}^2} - \dfrac{y_d{}^2}{2\sigma_{y_d}^2}\right), z_d = 0, \\ \dfrac{1}{2\pi\sigma_{y_d}\sigma_{z_d}} \exp\left(-\dfrac{y_d{}^2}{2\sigma_{y_d}^2} - \dfrac{z_d{}^2}{2\sigma_{z_d}^2}\right), x_d = 0, \end{cases} \tag{11}$$

where σ_{x_d}, σ_{y_d}, and σ_{z_d} are the mean square error of m warhead fragments formed by one projectile explosion, and m represents the intersection number of warhead fragments and target in the coordinate system $o_d x_d y_d z_d$ after the explosion of any projectile. However, not all m warhead fragments can cause damage to the target, which needs to be considered from the probability of m warhead fragments hitting the target and the weight coefficient of hitting the target key cabins.

For the m warhead fragments, the probability of a single warhead fragment hitting any point $P_s(x_d, y_d, z_d)$ in the j-th cabin is

$$P_s = \begin{cases} \displaystyle\int_{-l_1}^{l_1} \int_{-l_2}^{l_2} f(x_d, y_d) dx_d dy_d, z_d = 0, \\ \displaystyle\int_{-l_3}^{l_3} \int_{-l_4}^{l_4} f(y_d, z_d) dy_d dz_d, x_d = 0, \end{cases} \tag{12}$$

where $(-l_1, l_1)$ and $(-l_2, l_2)$ are the width and length range of the equivalent square plane of the j-th cabin of the target in the plane $x_d o_d y_d$, and $(-l_3, l_3)$ and $(-l_4, l_4)$ are the width and length range of the equivalent square plane of the j-th cabin of the target in the plane $y_d o_d z_d$; here, $(-l_2, l_2) = (-l_3, l_3)$.

The damage probability of the j-th cabin can be expressed by the following formula:

$$P^j = 1 - e^{-\frac{E^j}{m^j}}, \tag{13}$$

where m^j is the number of warhead fragments required for the damage of the j-th cabin, and E^j is the damage ratio of hitting the j-th cabin under m^j warhead fragments. m^j is determined by the number of warhead fragments in the plane $x_d o_d y_d$ and plane $y_d o_d z_d$. They are recorded as m_1^j and m_2^j, respectively. Therefore, $m^j = m_1^j + m_2^j$, m_1^j, and m_2^j are calculated by the following formula:

$$\begin{cases} m_1^j = \displaystyle\int_{-l_1}^{l_1} \int_{-l_2}^{l_2} \frac{m P_s(z_d = 0)}{4 l_1 l_2} dx_d dy_d, \\ m_2^j = \displaystyle\int_{-l_3}^{l_3} \int_{-l_4}^{l_4} \frac{m P_s(x_d = 0)}{4 l_3 l_4} dy_d dz_d. \end{cases} \tag{14}$$

The damage probability of the entire target can be calculated using the damage criteria for each cabin. Formula (15) is the damage probability of the entire target under m warhead fragments.

$$P = 1 - \prod_{j=1}^{N}\left(1 - P^j\right) = 1 - \prod_{j=1}^{N}\left(1 - \left(1 - e^{-\frac{E^j}{m^j}}\right)\right). \quad (15)$$

Formula (15) indicates that when calculating the damage probability of the warhead fragments formed by the explosion of the projectile fuze to the target in the air, it is necessary to consider the number of effective warhead fragments that hit the target and the damaging weight of each cabin of the target, which involves the warhead fragment position, the flight velocity of the warhead fragment that relative to the target, and the density of warhead fragment group. However, these factors are uncertain. How to convert these uncertain factors into known parameters using the mirror method, so that the interactive judgment conditions and damage calculation function can be fully used to directly obtain the damage result of the target, which is very critical.

6. Target Damage Efficiency Assessment Method with Uncertain Information Based on an Adaptive Fuzzy Neural Network

From the damaged cabin of the target, the damage efficiency result of the target is determined by the damage probability of each cabin. The target's final damage efficiency evaluation can be defined in terms of the probability and vulnerability weight of a warhead fragment striking any cabin. Formula (15) does not consider the specific vulnerability characteristics of each cabin. To describe the damage efficiency result of the whole target more scientifically, the vulnerability weight coefficient of each cabin can be introduced.

Assuming that the damage probability of the j-th cabin is P^j and its vulnerability weight is ω^j, j is the serial number of the cabin, $j = 1, 2, \cdots, N$, and N is the total number of the cabin. Then, the damage probability of the whole target can be described by the following formula:

$$P = \sum_{j=1}^{N} \omega^j P^j, \quad (16)$$

where $\omega = \omega^1 + \cdots + \omega^j + \cdots + \omega^N = 1$, ω is the whole vulnerability weight. The damage effectiveness will vary depending on the vulnerability of each cabin. Each compartment's warhead fragment density is divided into two directions: plane $x_d o_d y_d$ and plane $y_d o_d z_d$. For the j-th cabin, it can be converted to the relative coordinate system taking o_d as the center point through coordinate translation. Each cabin is regarded as a square body. Based on the intersection of cabins and warhead fragments formed by the projectile explosion, it can generally be summarized and concentrated on the planes $x_d o_d y_d$, $y_d o_d z_d$, and $x_d o_d z_d$. Figure 5(a) depicts the spatial intersection relationship between the warhead fragment and target after the projectile explosion, and Figure 5(b) depicts the division of the target's vulnerable damaged cabins.

According to the distribution of warhead fragments on the planes $x_d o_d y_d$, $y_d o_d z_d$, and $x_d o_d z_d$ in Figure 4, define the damage factor set $(X_d, Y_d, Z_d, G_j, F_j)$. Set (X_d, Y_d, Z_d) as the distance deviation of the warhead fragment group in three directions of the target coordinate system $o_d x_d y_d z_d$; G_j is the density of warhead fragments covering the j-th cabin, which is expressed by the ratio between the coverage area of warhead fragments to the j-th cabin and the whole area of the j-th cabin; F_j is the warhead fragment fire density hitting the j-th cabin, and it can be expressed by the ratio of the number of warhead fragments to the cross-sectional area of the target itself. These damage factors can be considered to be independent of each other. The damage effectiveness of the j-th cabin is recorded as R_j, and the corresponding damage probability is P^j. The mapping relationship between the five damage factors and the damage effectiveness cannot be expressed by a unified mathematical model for the damage degree of the j-th cabin. As a result, we propose to describe the damage effectiveness using an adaptive fuzzy neural network based on the Takagi-Sugeno model [28–31]. Depending on the selected computation rules, the fuzzy neural network has two main options for fuzzy inference models, one is the Mamdani fuzzy inference method, and the other is the Takagi-Sugeno fuzzy inference method. The Mamdani fuzzy inference method consists of three basic components, and they are input, fuzzy rules, and output, respectively. After variable input into the fuzzy inference system, the fuzzy rules contain a set of written fuzzy conditions that describe the system's output. Apply the rules, there will generate a fuzzy inference result. The Mamdani fuzzy inference method is highly useful in collecting and processing information, enabling faster inference of precise computational results [32]. Takagi and Sugeno developed the Takagi-Sugeno inference model in the 1980s, which is suitable for problems involving high dimensions and multiple fuzzy inference rules [33]. A typical two-dimensional input and one-dimensional output fuzzy system can be represented using "if-then" rules:

$$\begin{aligned} &\text{if } x_i \text{ is } \quad A_1^i, x_2 \quad is \quad A_2^i, \cdots, x_k \quad \text{is} \quad A_k^i, \\ &\text{then} \quad y_i = p_0^i + p_1^i x_1 + \cdots + p_k^i x_k, \end{aligned} \quad (17)$$

where A_k^i represents the fuzzy set of the fuzzy system, p_k^i represents the parameters of the fuzzy system, and y_i represents the output obtained based on the fuzzy rules.

The biggest difference between the Takagi-Sugeno fuzzy inference method and the Mamdani fuzzy inference method is that the Takagi-Sugeno fuzzy inference model lacks a defuzzification module because its inference result is already a crisp value. Moreover, it replaces the fuzzy implication relationship in the Mamdani controller with a crisp output function. By adopting the Takagi-Sugeno model, specific mathematical expressions can be used to express the damage effectiveness of the target in the output membership function layer of the fuzzy neural network.

The Takagi-Sugeno (T-S) fuzzy neural network model is divided into five layers, as illustrated in Figure 6.

The first layer is the input variable layer, and each node is directly connected to the input vector. The system has five input variables corresponding to five damage factors.

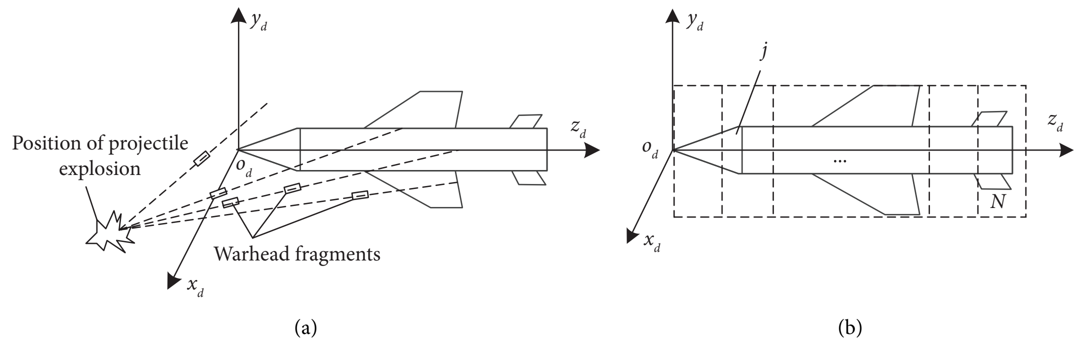


FIGURE 5: The spatial intersection relation of projectile-target intersection and target cabins division. (a) The spatial intersection relationship between the warhead fragment and target after the projectile explosion. (b) Schematic diagram of the division of vulnerable damaged cabins of the target.

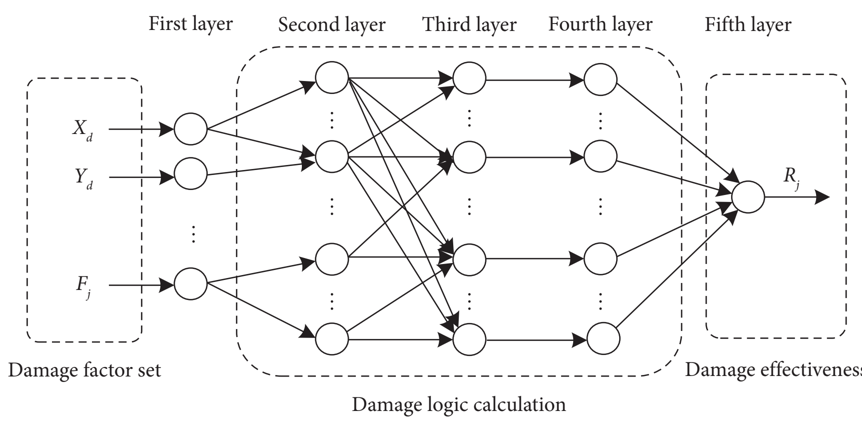


FIGURE 6: Simplified structure of adaptive fuzzy neural network system.

X_d, Y_d, Z_d, G_j, F_j are the measured values of the universe of five damage factors. The output of this layer is

$$O^1_{(n)} = u_n, \tag{18}$$

where $O^1_{(n)}$ is the output value of the k-th node, and u_n is the input variable. $\mathbf{u} = [u_1, \cdots, u_n]^{\mathrm{T}}$ is the input vector, n is the dimension of the input vector, $n = 1, 2, \cdots, 5$. That is, the five damage factors X_d, Y_d, Z_d, G_j, F_j are the five components of the input vector, respectively.

The second layer is the input membership function layer, in which each node represents a variable in the fuzzy lingual. Its function is to determine the degree to which each input component is a member of each fuzzy lingual variable [34, 35]. Each fuzzy lingual variable's membership function can be of any type, and this algorithm uses the Gaussian function. Then, the calculation method of the relative fuzzy set membership function of each input component is shown in the following formula:

$$O^2_{(n)} = \mu(u_n) = \exp\left[-\frac{(u_n - c_n)^2}{2\sigma_n{}^2}\right], \tag{19}$$

where c_n and σ_n are the antecedent parameters of ANFIS; $\mu(u_n)$ is membership function.

The reasoning rule layer is the third layer, and each node represents a fuzzy rule, which is required for fuzzy rule matching. The reasoning rule layer is responsible for multiplying the input signals to obtain the excitation intensity of fuzzy rules, which can be expressed by the following formula:

$$O^3_{(n)} = w_n = \prod_{n=1}^{5} O^2_{(n)}, \quad n = 1, 2, 3, 4, 5, \tag{20}$$

where $O^3_{(n)}$ is the incentive intensity of the rule corresponding to each node.

The fourth layer is the layer that contains the output membership function [36]. Each node corresponds to a particular membership function. Each output membership function is a Sugeno linear function of zero or first order used to calculate each rule's output. Assuming that the k-th inference rule is R_k and that its form can be described using the following formula:

$$\begin{aligned}&\text{if } X_d \text{ is } X_k \text{ and } Y_d \text{ is } Y_k \text{ and } Z_d \text{ is } Z_k \text{ and } G_j \text{ is } G_k \text{ and } F_j \text{ is } F_k,\\&\text{then } O^4_{(n)} = f_n = w_n\left(P_{k0} + P_{k1}X_d + P_{k2}Y_d + P_{k3}Z_d + P_{k4}G_j + P_{k5}F_j\right),\end{aligned} \tag{21}$$

where the part *if* is the precondition of fuzzy rules, X_k, Y_k, Z_k, G_k, F_k are the k-th fuzzy lingual variable of five damage factors, respectively, part *then* is the result of the judgment, and $P_{k0} - P_{k5}$ are the truth coefficients; that is, the output is a linear combination of input variables, but the coefficients are different for different rules.

The fifth layer is the output variable layer. It contributes to reducing ambiguity through the use of the weighted-average method [37, 38]. There is only one output variable, which is the damage effectiveness of the target R_j, which is obtained by the following formula:

$$O^5_{(n)} = R_j = \sum_{n=1}^{5} \overline{w_n} f_n = \frac{\sum_{n=1}^{5} w_n f_n}{\sum_{n=1}^{5} w_n}. \tag{22}$$

According to the Takagi-Sugeno fuzzy neural network model, the damage effectiveness R_j of the j-th cabin is calculated, and the total damage result can be expressed by formula (23) by introducing the weight of the target cabin.

$$R = \sum_{j=1}^{N} \omega_j R_j. \tag{23}$$

According to the target damage efficiency assessment model with an adaptive fuzzy neural network, the algorithm and procedure are as follows.

Step 1. Initialize the Takagi-Sugeno fuzzy neural network model. We use subtraction clustering to initialize this model. For K data points $(D_1, D_2, \cdots, D_K)$ in the multidimensional space, assuming that the data points have been normalized to a hypercube space, and define the value of the density function of the data point D_i as follows:

$$P_i = \sum_{j=1}^{K} \exp\left(\frac{-4\left\|D_i - D_j\right\|^2}{\delta_1}\right), \tag{24}$$

where δ_1 is a positive number.

We take the maximum density value point D_m as the first clustering center, whose density value is P_m, and recalculate the new density value by the following formula:

$$P_i^{'} = P_i - P_m \exp\left(\frac{-4\left\|D_i - D_m\right\|^2}{\delta_2}\right), \tag{25}$$

where δ_2 is also a positive number. Define a neighborhood radius where the density value decreases significantly. Obviously, the density value of data points near D_m decreases significantly. Therefore, it is unlikely to be selected as the next cluster center. Then, the cluster center with a relatively close distance is avoided, and in general, δ_2 is greater than δ_1, and $\delta_2 = \rho\delta_1$, ρ is empirical value, $\rho \in (1.2, 1.5)$, and the next cluster center can be selected. By this calculation method, the new density value of each point is repeatedly calculated until no new cluster center can be found according to a certain criterion. After we complete the clustering, an initial first-order Takagi-Sugeno model for all clustering centers can be obtained. A cluster center is equivalent to a rule. Because the number of fuzzy lingual values and the number of rules of the input and output vectors have been determined, what we need to learn is the coefficient of formula (21) and the center value and width of each membership function, which can be determined by the gradient descent algorithm. This way, the coefficient of formula (21) can be determined.

Step 2. According to the relative position of the projectile and target and the warhead fragment parameters in $o_d x_d y_d z_d$ after the projectile explosion, and the number of cabins of the target and the corresponding vulnerable weight coefficient, calculate the distribution density parameters of the warhead fragment in the two directions of the plane $x_d o_d y_d$ and $y_d o_d z_d$ by formula (11) and gain the distance deviation of the warhead fragment group in three directions of the target coordinate system, namely (X_d, Y_d, Z_d), and calculate the ratio G_j, F_j, and R_j.

Step 3. Based on the calculation parameters step (2), these parameters are used as input of the first layer of the Takagi-Sugeno fuzzy neural network model, and then, according to the process in Figure 6 and the calculation basis of formula (23), the target's damage effectiveness is determined.

The pseudocode of the Takagi-Sugeno fuzzy neural network of the damage effectiveness of the target is reported in Algorithm 1.

The flowchart of Takagi-Sugeno fuzzy neural network algorithm of the damage effectiveness of the target is shown in Figure 7.

In Figure 7, the left side shows the five layers of the adaptive fuzzy neural network, which includes the input variable layer of the first layer, the input membership function layer of the second layer, the reasoning rule layer of the third layer, the output membership function layer of the fourth layer, and the output variable layer of the fifth layer. The right side shows the output results obtained for each layer. After inputting the training set $(X_d, Y_d, Z_d, G_j, F_j)$ into the first layer, the output value $O^1_{(n)}$ of each node can be obtained through calculation. In the second layer, the input variables are fuzzified and converted into membership degrees of different fuzzy sets, and the membership function of the relative fuzzy set of each input component $O^2_{(n)}$ is obtained. The input signals from the second layer enter the third layer and are multiplied to obtain the excitation intensity $O^3_{(n)}$ of each fuzzy rule. Based on the excitation

Start of Algorithm
Inputs: The distance deviation of the warhead fragment group, the density of warhead fragments covering the cabin (X_d, Y_d, Z_d), the warhead fragment fire density hitting cabin (G_j), the ratio between the coverage area of warhead fragments and target (F_j)
Output: The damage effectiveness of the target (R_j)
Initialization:
(1) Initialize fuzzy rule base, initialize fuzzy controller parameters, initialize clustering parameters, and initialize the maximum number of fuzzy sets
(2) Cluster the input data set by a subtractive clustering algorithm to find all clustering centers by equations (24) and (25), generate the initial fuzzy rule base and fuzzy controller parameters
Steps:
(1) Convert input variables X_d, Y_d, Z_d, G_j, F_j into fuzzy sets by equation (18)
(2) Calculate the membership of input variables in each fuzzy set by equation (19)
(3) Use Takagi-Sugeno fuzzy reasoning method to obtain the incentive strength of fuzzy rules by equation (20)
(4) Calculate the reasoning results according to the fuzzy rule base and the input after fuzzification by equation (21)
(5) Use the weighted average defuzzification method to convert the fuzzy output into specific output values by (22)
(6) Output the damage effectiveness of the target R_j
End of Algorithm

ALGORITHM 1: Pseudocode of Takagi-Sugeno fuzzy neural network of the damage effectiveness of the target.

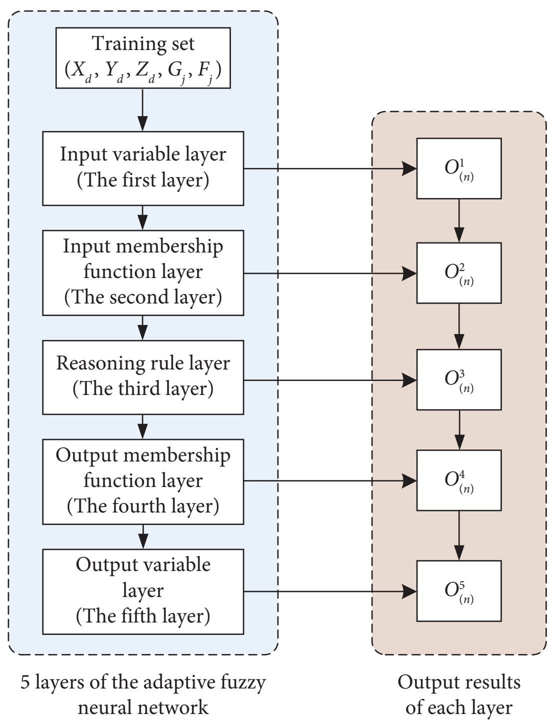


FIGURE 7: The structure of the Takagi-Sugeno fuzzy neural network of the damage effectiveness of the target.

intensity $O^3_{(n)}$ of each rule obtained from the third layer in all rule bases, the inference result $O^4_{(n)}$ of each rule is obtained through the inference calculation of the fourth layer. The fifth layer gets the specific output values $O^5_{(n)}$ after defuzzification the reasoning result of the fourth layer.

7. Calculation and Analysis

7.1. Damage Probability Calculation and Analysis. When an air defense antimissile strikes an air target, the optimal explosion position or distribution area can be calculated based on the characteristics of the warhead fragment damage element, the target vulnerability, and the fuze warhead coordination characteristics. When the projectile's fuze detonates in the optimal explosion point distribution area, the warhead fragment can precisely strike the target's most vulnerable area, resulting in maximum damage effectiveness. Due to the different intersection points between the projectile and the target, the warhead fragments also cover the target differently, resulting in a significant difference in the number of warhead fragments that can penetrate the target. When combined with the target's vulnerable cabins, the target's actual damage effectiveness is actually determined by the hit probability of warhead fragment and the damage weight factor of each cabin. According to the relationship of the projectile explosion's location, the target's location, and the ground coordinates, the only factors that can truly cause warhead fragments to strike the target are the projectile explosion's location and the target's location. Warhead fragments are scattered according to the projectile's intersection attitude with the target. In one test, to intuitively analyze the specific dispersion position of warhead fragments in the target coordinate space, according to the spatial relationship in Figure 3, take the target coordinate system $o_d x_d y_d z_d$ as the benchmark of the whole space system. That is, the point o_d is the origin, and its coordinate is $(0, 0, 0)$. The explosion proximity intersection tests of two groups of projectiles and targets were counted, with 20 projectiles in each group. According to the statistical probability method, the average position coordinates of the two projectile explosion centers are $(3.5, -4.8, -3.26)$ and $(1.57, -2.83, -1.44)$, respectively, and the unit is meter. The average angle of intersection between the projectile and the target is 5.8° and 11°, respectively. The static minimum and maximum dispersion directions of projectile-formed warhead fragments are approximately 31.2° and 35.5°, respectively. The projectile explosion produces 200 uniform equal-volume warhead fragments. The target is mainly divided into three cabins, electronic guidance cabins N_1, fuel explosive cabins N_2, and other cabins N_3. In the calculation, the damage weight factors ω^1, ω^2, and ω^3 are taken as 0.35, 0.65, and 0.1, respectively. The electronic guidance cabin is primarily damaged by warhead fragment hit, resulting in the loss of combat capability for the target's own electronic guidance, but it is not destroyed directly. The damage to the target's fuel explosive cabin is primarily caused by warhead fragments striking directly at the target's fuel explosive cabin, resulting in damage caused by the target ignition explosion. The number of warhead fragments required in this cabin is not large. As long as the kinetic energy of each warhead fragment reaches the power to penetrate the target, the target's damage effectiveness is maximized; in other cabins, the warhead fragment striking this position only modifies the target's flight state and does not cause fatal damage to the target.

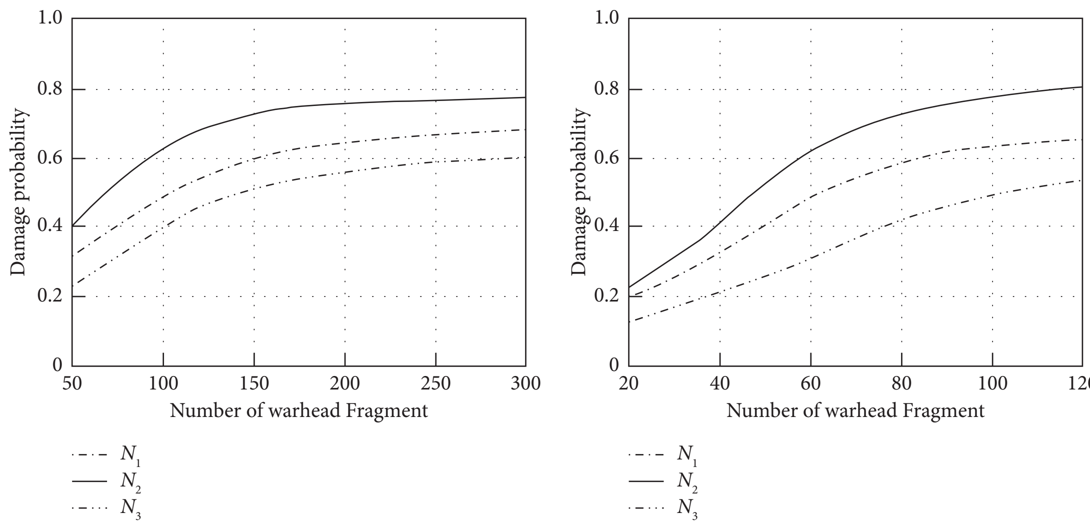
When the conditions for the intersection criterion are met, the damage probability of three cabins is calculated using formula (13). According to the two groups of tests, the mean square error of the dispersion position of each group of warhead fragments is counted and denoted as $({\sigma_{x_d}}^1, {\sigma_{y_d}}^1, {\sigma_{z_d}}^1)$ and $({\sigma_{x_d}}^2, {\sigma_{y_d}}^2, {\sigma_{z_d}}^2)$, respectively; among them, ${\sigma_{x_d}}^1 = 0.56$, ${\sigma_{y_d}}^1 = 0.25$, and ${\sigma_{z_d}}^1 = 1.21$; ${\sigma_{x_d}}^2 = 0.15$, ${\sigma_{y_d}}^2 = 0.25$, and ${\sigma_{z_d}}^2 = 0.23$. Based on the statistical mean square deviation of warhead fragment dispersion position, the damage probability $P_s(x_d, y_d, z_d)$ of each group of warhead fragments at $z_d = 0$ and $x_d = 0$ to three cabins is calculated, respectively, as shown in Figures 8 and 9.

As illustrated in Figures 8 and 9, the damage probability of the three cabins increases with the number of warhead fragments striking the target. On the other hand, the smaller the mean square error in the dispersion of warhead fragments, the greater the likelihood of the cabin being damaged. Under the same distribution of warhead fragments in $x_d o_d y_d$, Figure 10 illustrates the target damage probability under different coverage degree and distribution of warhead fragment using the set damage weight. In contrast, Figure 11 illustrates the target damage probability under different warhead fragment fire density and distribution using the set damage weight by formula (16).

It is not difficult to find when the damage weight factors of target were determined, the smaller the relative position of projectile and target, the stronger the fragment penetration ability of the target, and the more obvious the damage effect. The smaller the mean square error in the dispersion of warhead fragments, the greater the cabin being damaged. The larger the coverage density and fire density of warhead fragment, the greater the damage probability. These results are consistent with the trend of actual damage testing.

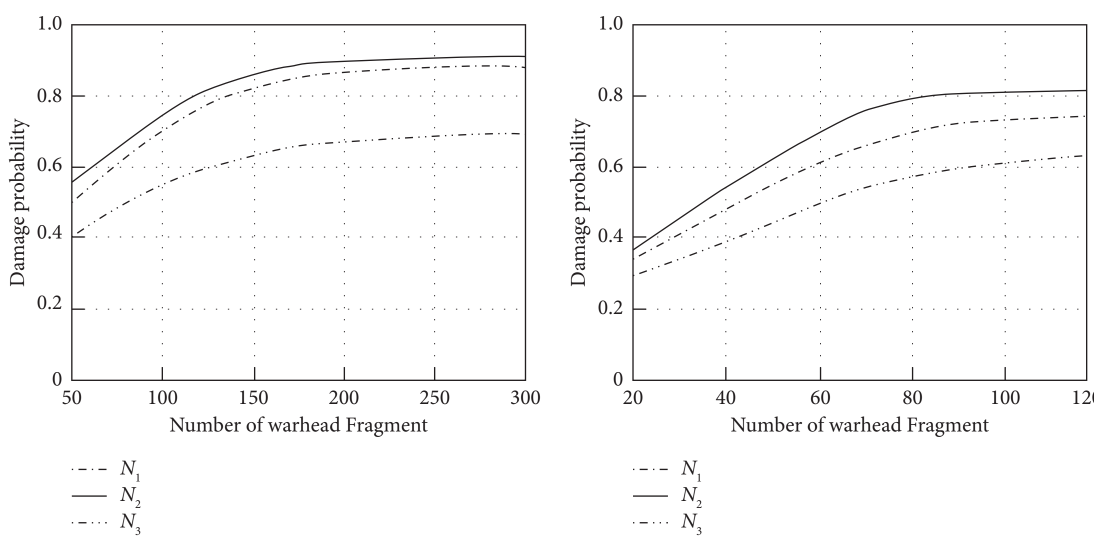
7.2. Numerical Calculation of Target Damage Effectiveness Based on an Adaptive Fuzzy Neural Network. Because the circular surface of the head part of the target is relatively small, the target is regarded as a cylinder and divided according to the electronic guidance cabin N_1, fuel explosive cabin N_2, and other cabins N_3. First, take the initial calculation of target damage parameters. Under the target coordinate system $o_d x_d y_d z_d$, it is defined that the centerline of each cabin is on $o_d z_d$, and the direction close to o_d point is the starting point of each cabin. Then, the coordinate positions of the starting points of the three cabins are $(0, 0, 0)$, $(0, 0, 0.6)$, $(0, 0, 1.6)$. The diameter of the target is 0.48 m, and the length is 4.5 m. The total area of each cabin is calculated according to the projection of the target on the planes $x_d o_d y_d$, $y_d o_d z_d$, and $x_d o_d z_d$. The total area of the three cabins is $0.288\,\mathrm{m}^2$, $0.48\,\mathrm{m}^2$, and $1.392\,\mathrm{m}^2$, respectively. Each cabin can take the o_d point as the central benchmark. In the simulation calculation, the mass of each warhead fragment is set as 15 g, and the warhead fragment cross-sectional area is $78.5 \times 10^{-3}\mathrm{m}^2$.

According to the structural reasoning of the adaptive fuzzy neural network, the damage effectiveness of each cabin is calculated from the damage factor set $(X_d, Y_d, Z_d, G_j, F_j)$ and the input layer, input membership function layer, reasoning rule layer, and the input parameters corresponding to the output variable layer of the adaptive fuzzy neural network. The damage effectiveness is determined by combining it with the damaging weight of each cabin. The number of uniform equal-volume warhead fragments formed by the projectile explosion is 200. The average intersection attitude angle between the projectile and target is 5.8°. The warhead fragments are evenly distributed at the projectile explosion position $(3.5, -4.8, -3.26)$ of the coordinate system $o_d x_d y_d z_d$. We calculate the damage probability using two factors of warhead fragment group coverage and warhead fragment fire density, as well as the



(a) (b)

Figure 8: Damage results of the first group of warhead fragments to three cabins. (a) Damage probability of three cabins at $z_d = 0$. (b) Damage probability of three cabins at $x_d = 0$.



(a) (b)

Figure 9: Damage results of the second group of warhead fragments to three cabins. (a) Damage probability of three cabins at $z_d = 0$. (b) Damage probability of three cabins at $x_d = 0$.

mapping relationship between damage probability and the degree to which a warhead fragment covers the cabin and the warhead fragment group fire density, as illustrated in Figure 12.

As illustrated in Figure 12, the adaptive fuzzy neural network can more accurately approximate the mapping relationship between damage effectiveness and damage factors, indicating that the adaptive fuzzy neural network has a high capacity for generalization. It is not difficult to determine that, once the damaging weight of each cabin is determined, the target's damage effectiveness is closely related to the number of warhead fragments in each cabin (coverage degree) and the density of effective warhead fragments penetrating the target (fire density). Correspondingly, the increase in the number of warhead fragments in each cabin can be reflected in the ratio G_j, which is denoted by the ratio of the area of the j-th cabin covered by warhead fragments to the area of the j-th cabin, and the ratio

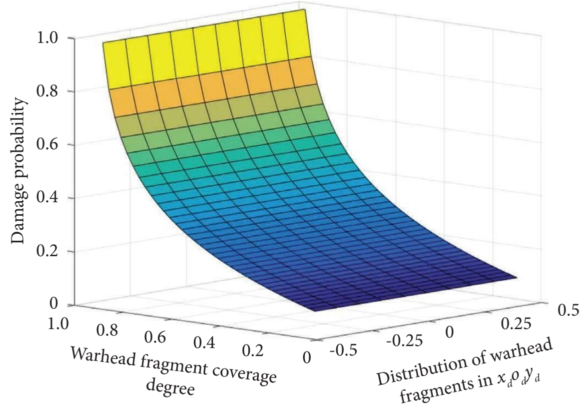


Figure 10: The target damage probability under different warhead fragment coverage degree and distribution.

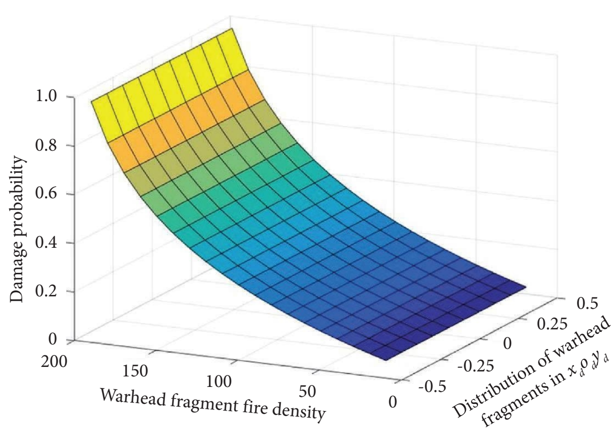


Figure 11: The target damage probability under different warhead fragment fire density and distribution.

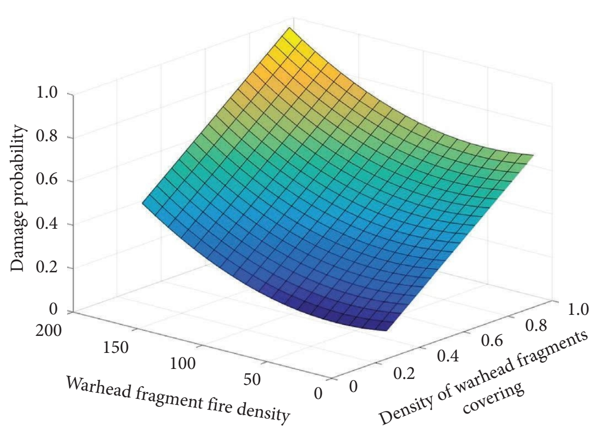


Figure 12: Schematic diagram of the relationship between damage effectiveness and the two damage factors.

F_j of the number of warhead fragments to the cross-sectional area of the target itself. The greater the ratios, the better the damage effectiveness.

7.3. Comparison and Analysis. This paper investigates the criterion and calculation method using shot-line technology. We develop a calculation model for target damage probability with multiple vulnerable cabins and an adaptive fuzzy neural network with damage factors as input variables. The computation model takes into account many factors, such as the target cabin's damage weight factor, the dispersion error of the warhead fragment striking the target, the warhead fragment coverage density, and the warhead fragment fire density. At the same time, we train, test, and calculate the data from the actual projectile-target intersection damage test using the established model. The model studied in this paper differs from the calculation method of target damage described in existing published literature. It considers the damage efficiency from the actual situation of the intersection of the projectile and target, involving the dispersion error of the warhead fragment, the warhead fragment coverage density, and the warhead fragment fire density. Especially, the proposed method takes into account the vulnerable factors of the different cabins of the target itself, and the calculated result is closer to the real damage effect.

In references [6, 7, 10, 17], some researchers have also proposed some scientific target damage calculation methods, which are mainly derived from more specific known parameters, such as the fuze real-time explosion point statistical method, a tree diagram airplane damage method, the warhead fragment hit probability, and Bayesian network parameter learning algorithm. To demonstrate the rationality and scientific basis of the algorithm and calculation model in this paper, we use the proposed damage calculation algorithm of this paper and algorithms of references [6, 7, 10, 17] to compare the damage results based on the state parameters of Figures 8 and 9. Tables 1 and 2 are the comparative calculation results of missile target intersection according to different damage calculation methods.

Tables 1 and 2 show the comparative results of calculating the probability of target damage based on the average explosion position (3.5, −4.8, −3.26) and (1.57, −2.83, −1.44) of two groups of projectiles and the average attack angle of 5.8° and 11°. Reference [6] utilized the fuze real-time explosion point statistical method, which focuses primarily on the explosion dispersion parameters of the projectile and disregards the damaging weight of the target itself. It treats the entire target as having the same damage weight and calculates damage based solely on the ratio of the area formed by warhead fragments scattered on the target surface to the total target surface area. This method reflects only one side of the relationship between the number of warhead fragments and the probability of damage, which is proportional to the number of warhead fragments. Reference [7] uses a tree diagram airplane damage method, which is a method for calculating damage based on the internal damage level of the target calculated from the top down. Currently, it is also a more realistic calculation method, particularly for evaluating aircraft target damage. However, this method necessitates knowledge of the damaged relationship between all components, and the calculation method is complex. For the damage effectiveness evaluation

Table 1: The comparative calculation results when the average position coordinates of projectile explosion centers are (3.5, −4.8, −3.26) and the average angle of intersection between the projectile and the target is 5.8°.

Damage cabins	Damage probability				
	Method in reference [6] (%)	Method in reference [7] (%)	Method in reference [10] (%)	Method in reference [17] (%)	Proposed method (%)
(0, 0, 0~0, 0, 0.6)	57.8	57.3	56.6	58.2	61.4
(0, 0, 0.6~0, 0, 1.6)	59.1	62.6	67.9	70.7	74.2
(0, 0, 1.6~0, 0, 4.5)	51.7	54.2	55.8	51.6	53.5
Total target damage probability	56.2	58.0	60.1	60.2	75.0

Table 2: The comparative calculation results when average position coordinates of projectile explosion centers are (1.57, −2.83, −1.44), and average angle of intersection between the projectile and the target is 11°.

Damage cabins	Damage probability				
	Method in reference [6] (%)	Method in reference [7] (%)	Method in reference [10] (%)	Method in reference [17] (%)	Proposed method (%)
(0, 0, 0~0, 0, 0.6)	58.5	60.4	59.8	63.9	69.2
(0, 0, 0.6~0, 0, 1.6)	68.3	72.6	70.8	70.2	81.4
(0, 0, 1.6~0, 0, 4.5)	53.2	55.3	54.6	58.7	53.1
Total target damage probability	60.0	62.7	61.7	64.3	82.3

of the warhead fragment group formed by the projectile explosion intersecting with the target in the air, the top-down relationship of each component of the damaged target is not very obvious. The objective of the target damage evaluation model of the adaptive fuzzy neural network presented in this paper is to evaluate the damage under the condition that the number of warhead fragments hitting each target component is unclear. The method described in reference [7] for calculating the probability of damage is relatively close to that described in this paper. However, for the damage probability between the target cabins of (0, 0, 0.6) and (0, 0, 1.6) attacked by warhead fragments, the damage probability calculated by the proposed method in this paper is slightly higher than that in Reference [7]. This is primarily due to the fact that the damaging effect is calculated based on the actual vulnerability weight of the target. In the interval between (0, 0, 0.6) and (0, 0, 1.6), the vulnerability weight is as high as 0.65, meaning that even if a small number of warhead fragments strike the target, the probability of total damage is the highest. Reference [10] uses the probability that a fragment of the warhead will hit the target to determine the effect on the target's damage. This method assesses damage based on the ratio between the damaged area created by the warhead fragment penetrating the target surface and the total target surface area. This method is basically similar to the calculation result in reference [6]. The difference is that this method considers the conditional probability of the warhead fragment hitting the target under limited conditions. Obviously, the calculated damage probability is less than that in reference [6], but when the same warhead fragment attacks the same target area, such as the damage probability of the target cabin (0, 0, 0.6~0, 0, 1.6), the calculated damage probability in reference [6] is significantly less than that in this paper. Although the Bayesian network parameter learning algorithm is introduced in reference [17], which is based on the conditional of the prior probability of warhead fragments striking the target, the random probability multiattribute scheme ranking method is used to evaluate the target damage level, which is also a reasonable method for evaluating target damage. But the multiattribute ranking determined by this method must take into account additional factors, such as the central weight vector of target damage, and damage level. It is also necessary to take into account various factors of the target damage level membership function, which are characterized by a high degree of randomness in the evaluation and cannot be described by specific numerical values. The adaptive neural network target damage assessment method proposed in this paper takes a number of factors into account, including the decision condition of the intersection of warhead fragments and target, the vulnerable weight of target cabins, the location dispersion error of warhead fragments attacking the target, and the fire intensity of warhead fragments attacking. These parameters can be obtained directly during the experiment, eliminating the influence of many fuzzy parameters on target damage assessment. The parameters of each layer of the fuzzy neural network model can be directly calculated, particularly the parameters of the Takagi-Sugeno model initialized by the introduced subtractive clustering, and some parameters are unique, so this method can more accurately reflect the actual target damage effect, which is more intuitive to evaluate. By calculation and comparative analysis, when the average position coordinates of projectile explosion centers are (3.5, −4.8, −3.26) and the average angle of intersection between the projectile and the target is 5.8°, total target damage probability is 75%; when average position coordinates of projectile explosion centers are (1.57, −2.83, −1.44) and average angle of intersection between the projectile and the target is 11°, total target damage probability is 82.3%. The results show the smaller the distance between projectile and target, as well as the smaller the average intersection angle, and the larger the weight coefficient of the warhead fragment covering the target cabin, the total probability of the target damage increases obviously. In the two experimental calculations, the target cabin with the largest weight coefficient was considered, and compared with the existing literature, the damage probability of the proposed calculation method was increased by 9.13% and 10.93%, respectively, and it is clear that the proposed target damage assessment method can effectively reflect the real target damage effectiveness in the state of projectile and target intersection.

Through the above calculation and analysis, the target damage calculation method proposed in this paper considers the dispersion error and coverage density, fire density of warhead fragment, the target cabin's damage weight factor, and the ratio of the number of warhead fragments to the cross-sectional area of the target and sets up a new mathematical model for assessing the effectiveness of target damage, which can solve the problem of uncertainty in the evaluation and calculation of the target damage that caused by projectile explosion under random projectiles rendezvous. According to the damage weight of the target itself to balance and calculate the damage effect, one is to reflect the method proposed in this paper not only consider the importance of the target's own cabin components but also can judge the damage result from the weight of the target's own cabin, and rather than simply using the average breakdown area of each compartment to calculate the damage result, this is an advantage of the research method in this paper. The other is that in the damage calculation model based on the adaptive fuzzy neural network system mechanism, the damage probability of each target damaged cabin is considered under the weight factor of the target itself, and rather than simply using the average weight coefficient of each cabin to calculate the damage result, it is closer to the real situation of the real warhead fragment attack target state, so this is another advantage of the selected models and algorithms. Based on the data in Tables 1 and 2, it can be seen that, after defining the damage factor of the target itself and the damage weight of the cabin, it is obvious that the total damage probability becomes larger. The main reason is that the important part of the target where warhead fragments hit the target is the area with the highest damage weight, so the damage probability is larger than that calculated in the existing literature, which is also a more objective reflection of the real damage effect. Of course, the proposed method also has some shortcomings; for example, the calculation model does not consider the attenuation coefficient of projectile and target flight speed nor does it consider the control behavior factors of missile targets. In the future work, it is necessary to explore and study various capability control factors in the flight state of projectile and target intersection.

8. Conclusions

This paper discusses and researches a new target damage effectiveness assessment calculation method, analyzes the space coordinate system of projectile, target, and ground, and uses the target position as the center of the damage effectiveness calculation system. We establish the damage probability model of multiple warhead fragments hitting the target based on the warhead fragment distribution mechanism if the warhead fragments meet the conditions of hitting the target cabin. By introducing the damage factors, we give an evaluation and calculation method of target damage effectiveness based on an adaptive fuzzy neural network, and the designed method can truly reflect the effect of target damage in the field of air defense intercepting targets, and through the establishment of target damage model and parameter calculation and analysis, the following conclusions are obtained:

(1) In the target damage of projectile and target intersection, the explosion position of the projectile and the fragment group dispersion parameters are the important characteristic parameters, which can directly affect the result of the target damage. The smaller the relative position of projectile and target, the stronger the fragment penetration ability of the target, the more obvious the damage effect.

(2) The main factors of target damage include the target cabin's damage weight factor, the dispersion error and coverage density and fire density of warhead fragment, and the ratio of the number of warhead fragments to the cross-sectional area of the target, and these variables are embodied as fuzzy input variables, which can be transformed into a deterministic objective function by using adaptive fuzzy neural network, which can be used to characterize the damage effect of air defense intercepting targets. When the damage weight factors of target were determined, the smaller the mean square error in the dispersion of warhead fragments, the greater the cabin being damaged. The larger the coverage density and fire density of warhead fragment, the greater the damage probability. Through experimental data and simulation calculation, the results demonstrate that the model for calculating target damage effectiveness based on the adaptive fuzzy neural network proposed in this paper is suitable for evaluating conventional target damage at the projectile and target intersection in air defense interception.

(3) The damage test site can be used to obtain the parameters for the damage factors in the calculation model. Compared with the damage calculation methods proposed in other kinds of literature, the results also show that the calculation results of the proposed algorithm and calculation model are closer to the actual damage test results. This also reflects that the proposed damage calculation method of the adaptive neural network model can reflect the target damage assessment effectiveness under the intersection of antiaircraft interceptor projectile and target and provide a new idea for the subsequent research on the target damage under the cooperation of multiple projectiles. Additionally, the research model presented in this paper can be used to develop a new method for calculating the damage effectiveness of intelligent ammunition that is static or dynamic.

The research of target damage effectiveness evaluation involves many fields, such as weapon damage science, missile flight mechanics, and computer application. In the future, target damage evaluation will be a comprehensive application and development of knowledge in many fields with wide application prospects. Especially in the target damage effectiveness evaluation of a space air defense intercept under projectile and missile target space intersection, it reflects that the future air combat must face the development trend, in addition to the need to consider the structural characteristics of projectile explosion, explosion control method, and warhead fragment characteristic parameters, but also involves the intercept of the incoming target flight state and the target's own damage elements, so the target damage in space projectile and target intersection is a complex evaluation system.

Although this paper takes into account the dispersion error and coverage density and fire density of warhead fragment, and the target cabin's damage weight factor, develops a new mathematical model for assessing the effectiveness of target damage using an adaptive fuzzy neural network system, and demonstrates the calculation method, in the future work, it is necessary to consider the damage effectiveness of multiprojectile cooperative attack target, and the effectiveness of multiprojectile cooperative detection, control, and proximity explosion will be the research content in the need of target damage assessment, and it is also the future target damage assessment system that needs to develop the focus of research direction.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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