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An Effective Threat Evaluation Algorithm for Multiple Ground Targets in Multi-target and Multi-weapon Environments

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ABSTRACT

In an environment where a large number of weapons are operated compared to a large number of ground targets, it is important to monitor and manage the targets to set up a fire plan, and through their multilateral analysis, to equip them with a priority order process for targets having a high threat level through the quantitative calculation of the threat level. Existing studies consider the anti-aircraft and anti-ship targets only, hence, it is impossible to apply the existing algorithm to ground weapon system development. Therefore, we proposed an effective threat evaluation algorithm for multiple ground targets in multi-target and multi-weapon environments. Our algorithm optimizes to multiple ground targets by use of unique ground target features such as proximity degree, sorts of weapons and protected assets, target types, relative importance of the weapons and protected assets, etc. Therefore, it is possible to maximize an engagement effect by deducing an effective threat evaluation model by considering the characteristics of ground targets comprehensively. We carried out performance evaluation and verification through simulations and visualizations, and confirmed high utility and effect of our algorithm.

Key words: *Threat Evaluation, Threat Level, Fire Plan, Multiple Ground Target and Ground Weapon System.*

1. INTRODUCTION

In the environment where a large number of weapons are operated against a large number of ground targets, it's specially important to set up a fire plan for effectively suppress a large number of targets just in time, and apply it to military operations. In addition, it's essential to surveil and manage targets to set up a fire plan, and through the multilateral analysis of them, to be equipped with the process of giving a priority order to the targets having a high threat level by calculating the threat level quantitatively. Also, it is important to maximize an engagement effect by setting up an effective fire plan, which makes it possible to rapidly suppress the targets with a high deduced priority order.

As a part of the research on a fire plan for an effective target shooting, the research on a threat evaluation technique is actively in progress [1]-[17]. In the existing a threat evaluation techniques, there exists only the threat evaluation method targeting anti-aircraft and anti-ship targets, and due to the failure to present a threat evaluation method in the light of the characteristics of ground targets, especially plural ground targets, it's impossible to apply the existing method to ground weapon system development. Particularly, in the existing evaluation method targeting anti-aircraft targets, a threat evaluation has been performed on the basis of object variables such as target location, moving speed of a target, attack probability of a target deduced on the basis of the azimuth, distance between a target and assets, and properties of enemy air vehicles, etc.

In addition, in the threat evaluation techniques targeting the existing anti-ship target, it has relied on object variables such as target location, moving speed of a target, the distance to the shortest proximity point between a target and own ship, and arrival time, etc., and the existing techniques like this have been specialized in anti-aircraft & anti-ship areas, thus making it difficult to apply them to the threat evaluation of the ground targets. Unlike the anti-aircraft/anti-ship areas which think much of the moving speed and arrival time of a target, there is a need for a threat evaluation method optimized to ground targets in the light of unique features like proximity degree of a target, sorts of targets, importance of targets, and threat forms

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of targets, etc. for a proper evaluation of the threat level of ground targets.

This paper proposes an effective threat evaluation algorithm for multiple ground targets in multi-target and multi-weapon environments. Concretely, this paper proposes an effective threat evaluation algorithm in the light of unique features of ground targets such as proximity degree, sorts of weapons and protected assets, target types, and relative importance of weapons and protected assets, etc. in the proposed algorithm. This paper proposes the threat evaluation algorithm for multiple ground targets with the aim of deducing a threat level in a quantitative numerical value by reflecting characteristics of plural objects like targets, weapons and protected assets, and the object variables specialized in ground system development environment as base data for a fire plan calculation for the purpose of effectively suppressing a large number of ground targets in a short time in formula modeling. The proposed algorithm calculates a threat level of a target in the light of target type by setting up weighted value consequent on the importance of weapons and protected assets after carrying out proximity degree operations by taking into account the sorts of targets and protected assets. This paper carries out a threat evaluation of all targets by performing a threat level calculation process like this for all targets.

The remainder of this paper is organized as follows. In section II, this paper explains the limitations of the existing researches, and the objective of this research. In section III, this paper presents the system model considered in this paper, and in section IV, this paper describes the proposed threat evaluation algorithm. In section V, this paper shows excellence of the proposed technique through the performance evaluation, and lastly, in section VI, this paper presents its conclusion, and the follow-up research direction.

2. RELATED WORKS

The general process of the fire plan algorithm in the existing research is roughly comprised of two stages [1]-[3]. The first is the threat evaluation stage for targets, in which a threat is evaluated based on diverse characteristics in order to protect friendly forces assets from the threat of attacks of enemy forces assets, and a quantified threat, from which a quantified threat level is deduced in figures. The second stage is the one for carrying out weapon assignment with the aim of maximizing enemy forces damage by hitting enemy forces' assets through the minimum friendly forces weapon, and assignment between target and weapon is deduced on the basis of the previously deduced threat level.

As a part of a fire plan research for effective firing at a target, the research on a threat level evaluation technique [4]-[17] and weapon assignment technique(this paper leaves it out of the question) is actively in progress. The threat level evaluation is the first important stage of a fire plan as the process of evaluating the threat level of a target. Therefore, an inappropriate evaluation of a threat level comes to designate a misguided priority order in firing, weakening threat responsiveness [1]-[4]. Generally, a threat is evaluated by the combination of a strike capability, intention and proximity degree of a target [5]-[7], [10]. The strike capability of a target is the ability to inflict damage on assets, and the intention of a target means a will, or determination to inflict such damage [5]-[7]. The strike capability of a target is represented using variables such as a kind and speed of a target while the intention of a target is represented using motor mechanics, conduct of operation status, speed and advanced information of a target. The proximity degree of a target is represented using mostly the variables such as CPA(Closest Point of Approach), TCPA(Time to CPA), and TBH(Time before Hit), etc. [10].

The representative techniques related to a threat level evaluation includes artificial neural network-based technique [8], [9], Bayesian inference-based technique [10]-[12], and Fuzzy logic-based technique [13]-[16], etc. Bayesian inference-based threat evaluation technique calculates the final threat level by combining conditional probability using the occurrence probability of each threat evaluation element based on conditional probability. This technique has a merit of comparatively higher accuracy, but it has the critical point that a thorough verification process is required when defining conditional probability between elements. Fussy logic-based threat evaluation technique is advantageous to the expression of a change in a value consequent on weighted value and associative relation of each variable, and it calculates a threat level by considering the influencing degree on a threat level consequent on the condition of required variables for calculation. This technique has a merit of low complexity and easy implementation, but it has the critical point that its accuracy is lower than Bayesian inference-based threat evaluation technique.

However, the previously presented threat evaluation algorithm is a threat evaluation method targeting anti-aircraft and anti-ship targets. Particularly, the aforementioned threat evaluation methods carry out a threat evaluation based on object variables such as probability of attacks, imminent arrival degree, and flight path of the target which was deduced based on moving speed and approach angle of a target, and characteristic of enemy air vehicles, etc., so it is difficult to apply such threat evaluation techniques to the threat level analysis of multiple ground targets, in which an approach angle, imminent arrival degree, and flight path, etc. cannot be defined. As mentioned above, the existing threat evaluation techniques are targeting anti-aircraft and anti-ship targets, so there is a limit in applying these techniques to a ground weapon system development. Conclusively, these evaluation techniques are not fit enough to effectively suppress multiple ground targets; in this context, this paper is conducting the research on the threat evaluation algorithm for multiple ground targets.

3. SYSTEM MODEL

This paper is based on the following system model (battlefield environment). In the earth centered earth fixed coordinate system (ECEF; Earth Centered Earth Fixed), the location of the entire targets can be represented as the matrix $\mathbf{T}$ shown in Eq. (1) when the number of the entire targets is T_{Nm}.

$$\mathbf{T}=\begin{bmatrix} t_{1x} & t_{1y} & t_{1z} \\ t_{2x} & t_{2y} & t_{2z} \\ \vdots & \vdots & \vdots \\ t_{ix} & t_{iy} & t_{iz} \\ \vdots & \vdots & \vdots \\ t_{\mathrm{T_{Nm}}x} & t_{\mathrm{T_{Nm}}y} & t_{\mathrm{T_{Nm}}z} \end{bmatrix} \tag{1}$$

Here, the matrix $\mathbf{T}$ of the locations of the entire targets has the size of $(\mathrm{T_{Nm}}\times 3)$, and t_{ix} represents x coordinate of the i th target, t_{iy} represents y coordinate of the i th target, and t_{iz} represents z coordinate of the i th target. Therefore, the location of the i th target can be represented as $\mathbf{v}_i=\left[t_{ix},t_{iy},t_{iz}\right]$, which is the i th row vector of the matrix $\mathbf{T}$ of the locations of the entire targets.

When the number of the entire weapon groups is $\mathrm{B_{Nm}}$ and if the number of available weapons in the b th weapon group g_b is L_{g_b}, the number of the entire available weapons is $\sum_{b=1}^{\mathrm{B_{Nm}}}\mathrm{L}_{g_b}=\mathrm{L_{Nm}}$, and the location of the entire weapons can be represented as the matrix $\mathbf{L}$ shown in Eq. (2).

$$\mathbf{L}=\begin{bmatrix} l_{1x} & l_{1y} & l_{1z} \\ l_{2x} & l_{2y} & l_{2z} \\ \vdots & \vdots & \vdots \\ l_{jx} & l_{jy} & l_{jz} \\ \vdots & \vdots & \vdots \\ l_{\mathrm{L_{Nm}}x} & l_{\mathrm{L_{Nm}}y} & l_{\mathrm{L_{Nm}}z} \end{bmatrix} \tag{2}$$

Here, the matrix $\mathbf{L}$ of the locations of the entire targets has the size $(\mathrm{L_{Nm}}\times 3)$ with l_{jx} representing x coordinate of the j th weapon, l_{jy} representing y coordinate of the j th weapon, and l_{jz} representing z coordinate of the j th weapon. Therefore, the location of the j th weapon can be represented by $\mathbf{w}_j=\left[l_{jx},l_{jy},l_{jz}\right]$, which is the j th row vector of matrix $\mathbf{L}$ of locations of the entire weapons.

When the number of total protected assets is A_{Nm}, the location of total protected assets can be represented in matrix $\mathbf{A}$ equal to Eq. (3).

$$\mathbf{A}=\begin{bmatrix} a_{1x} & a_{1y} & a_{1z} \\ a_{2x} & a_{2y} & a_{2z} \\ \vdots & \vdots & \vdots \\ a_{kx} & a_{ky} & a_{kz} \\ \vdots & \vdots & \vdots \\ a_{\mathrm{A_{Nm}}x} & a_{\mathrm{A_{Nm}}y} & a_{\mathrm{A_{Nm}}z} \end{bmatrix} \tag{3}$$

Here, location matrix $\mathbf{A}$ of total protected assets has $(\mathrm{A_{Nm}}\times 3)$ size, and a_{kx} means x coordinate of the k th protected asset, a_{ky} means y coordinate of the k th protected asset, and a_{kz} means z coordinate of the k th protected asset. Accordingly, the location of the k th protected asset can be represented as $\boldsymbol{u}_k=\left[a_{kx},a_{ky},a_{kz}\right]$ which is the k th row vector of total protected assets location matrix $\mathbf{A}$.

The distance between the i th target and the j th weapon, d_{t_i,l_j}, can be represented as in Eq. (4).

$$d_{t_i,l_j}=\left\|\mathbf{v}_i-\mathbf{w}_j\right\| \tag{4}$$

The distance d_{t_i,a_k} between the i th target and the k th protected asset can be represented as Eq. (5).

$$d_{t_i,a_k}=\left\|\mathbf{v}_i-\boldsymbol{u}_k\right\| \tag{5}$$

4. PROPOSED ALGORITHM

This section proposes the threat evaluation algorithm for multiple ground targets in multi-target and multi-weapon environments. The existing threat evaluation techniques have been involved in the threat evaluation method targeting anti-aircraft and anti-ship targets, so there is a limit in applying these techniques to ground weapon system development. This paper proposes the threat evaluation algorithm for multiple ground targets with the aim of deducing the threat level in quantitative figures by reflecting the characteristics of plural objects like targets, weapons and protected assets, and object variables specialized in the ground system development environment in formula modeling as base data for calculating a fire plan for the purpose of effectively suppressing a large number of ground targets in a short time.

Fig. 1 shows the proposed threat evaluation algorithm flow chart. The proximity degree operations between target i in the light of sorts of weapons and all weapons, and the proximity degree operations between target i in the light of sorts of protected assets and all protected assets are carried out. Afterwards, weighted value consequent on the importance of weapons and protected assets is set up, and the threat level of target i in the light of the weighted value consequent on target type is calculated. The threat evaluation of all targets is completed by carrying out such a threat level calculation process for all targets.

Fig. 2 shows an example of the proposed algorithm. Fig. 2(a) gives an explanation by supposing the battlefield situation where there are 14 targets, 7 weapons. Fig. 2(b) shows that it's possible to find the priority order of 14 targets on the basis of the calculated threat value after carrying out the threat evaluation in the light of unique features of a large number of ground targets, such as the proximity degree, sorts of targets, relative importance of weapons and protected assets, and threat forms of targets, etc.

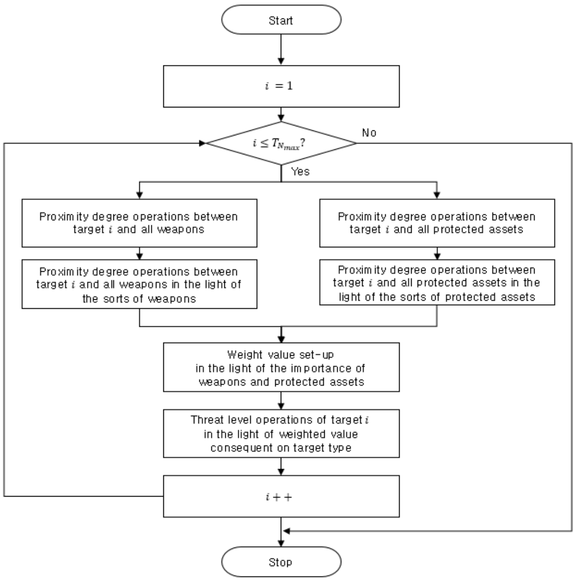
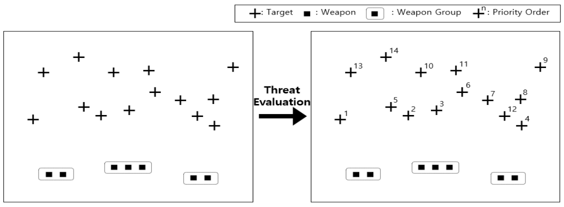


Fig. 1. Flow chart of the proposed algorithm



(a) (b)

Fig. 2. An example of the proposed algorithm

The proximity degree $D_{t_i,l}$ between the i th target and weapons in the light of weighted value $w_{l_j}\left(0 < w_{l_j} \le 1\right)$ consequent on the sort of the j th weapon can be represented as Eq. (6).

$$D_{t_i,l} = \frac{1}{L_{Nm}}\sum_{j=1}^{L_{Nm}}\frac{1}{w_{l_j}}\frac{d_{t_i,l_j}}{d_{\max_{t_i,l}}} \tag{6}$$

This means that the distance d_{t_i,l_j} between the i th target and the j th weapon is in proximity, and the bigger the weighted value w_{l_j} consequent on the sort of the j th weapon, the smaller figures the $D_{t_i,l}$ comes to get. The maximum distance $d_{\max_{t_i,l}}$ between the i th target and all weapons is as in Eq. (7).

$$d_{\max_{t_i,l}} = \max_{1\le j\le L_{Nm}}\left\{d_{t_i,l_j}\right\} \tag{7}$$

The proximity degree $D_{t_i,a}$ between the i th target and protected assets in the light of the weighted value $w_{a_k}\left(0 < w_{a_k} \le 1\right)$ consequent on the sort of the k th protected asset is as in Eq. (8).

$$D_{t_i,a} = \frac{1}{A_{Nm}}\sum_{k=1}^{A_{Nm}}\frac{1}{w_{a_k}}\frac{d_{t_i,a_k}}{d_{\max_{t_i,a}}} \tag{8}$$

This means the distance d_{t_i,a_k} between the i th target and the k th protected asset is in proximity, and the bigger the weighted value w_{a_k} consequent on the sort of the k th protected asset, the smaller figures $D_{t_i,a}$ comes to get. The maximum distance $d_{\max_{t_i,a}}$ between the i th target and all protected assets can be represented as Eq. (9).

$$d_{\max_{t_i,a}} = \max_{1\le k\le A_{Nm}}\left\{d_{t_i,a_k}\right\} \tag{9}$$

There is a need to consider both the proximity degree between targets consequent on the sort of weapons and weapon and the proximity degree between targets consequent on the sort of protected assets and protected assets. In case the weighted value representing the importance of weapon is $w_p\left(0 \le w_p \le 1\right)$, the importance of protected assets can be represented as $\left(1 - w_p\right)$. Accordingly, the proximity degree representing the relative importance of weapon and protected assets as the weighted value sum is as in Eq. (10).

$$\begin{aligned} D_{t_i} &= w_p D_{t_i,l} + \left(1 - w_p\right) D_{t_i,a} \\ &= w_p \frac{1}{L_{Nm}}\sum_{j=1}^{L_{Nm}}\frac{1}{w_{l_j}}\frac{d_{t_i,l_j}}{d_{\max_{t_i,l}}} + \left(1 - w_p\right)\frac{1}{A_{Nm}}\sum_{k=1}^{A_{Nm}}\frac{1}{w_{a_k}}\frac{d_{t_i,a_k}}{d_{\max_{t_i,a}}} \end{aligned} \tag{10}$$

In case the weighted value of weapon is 1($w_p = 1$) in Eq. (10), it is the same as Eq. (11), belonging to the case of minimization of survival probability of a target, and such a formula representation is used in case of no need for consideration of protected assets.

$$\begin{aligned} D_{t_i} &= w_p D_{t_i,l} \\ &= w_p \frac{1}{L_{Nm}}\sum_{j=1}^{L_{Nm}}\frac{1}{w_{l_j}}\frac{d_{t_i,l_j}}{d_{\max_{t_i,l}}} \end{aligned} \tag{11}$$

In case the weighted value of protected assets is 1($w_p = 0$) in Eq. (10), it is the same as Eq. (12), belonging to the case of consideration of survival probability of protected assets by top priority, and such a formula is used in case of no need for consideration of weapon survival.

$$\begin{aligned} D_{t_i} &= D_{t_i,a} \\ &= \frac{1}{A_{Nm}}\sum_{k=1}^{A_{Nm}}\frac{1}{w_{a_k}}\frac{d_{t_i,a_k}}{d_{\max_{t_i,a}}} \end{aligned} \tag{12}$$

The target weighted value consequent on a threat form is determined by the target striking distance, and sorts of targets, etc., and in case the target weighted value consequent on the threat form of the i th target is w_{t_i} , the threat level E_{t_i} of the i th target is as in Eq. (13).

$$\begin{aligned} E_{t_i} &= \frac{w_{t_i}}{D_{t_i}} \\ &= \frac{w_t}{w_p D_{t_i,l} + \left(1-w_p\right) D_{t_i,a}} \qquad (13) \\ &= \frac{w_t}{w_p \frac{1}{L_{Nm}} \sum_{j=1}^{L_{Nm}} \frac{1}{w_{l_j}} \frac{d_{t_i,l_j}}{d_{\max_{t_i,l}}} + \left(1-w_p\right) \frac{1}{A_{Nm}} \sum_{k=1}^{A_{Nm}} \frac{1}{w_{a_k}} \frac{d_{t_i,a_k}}{d_{\max_{t_i,a}}}} \end{aligned}$$

It means that the smaller the proximity degree D_{t_i} value in the light of the relative importance of weapons and protected assets, and the bigger the weighted value w_{t_i} of the i th target, the bigger the value the threat level E_{t_i} of the i th target comes to have.

The threat level operations is repeatedly performed through Eq. (6) ~ Eq. (13) of all targets($1 \le i \le T_{Nm}$), and threat levels of total targets are calculated.

Accordingly, it's possible to calculate the threat level for multiple ground targets through comprehensive consideration of the characteristics of ground targets by improving the limit in applying ground weapon system development of the existing threat evaluation techniques through the threat evaluation algorithm for multiple ground targets as above.

5. PERFORMANCE EVALUATION

In this section, performance evaluation and validation have been performed for the proposed algorithm through simulations and visualizations to prove the excellence of the proposed algorithm. The simulation has been performed by constructing virtual battle field environment as shown in Table 1 based on Matlab R2016a [18].

Table 1. Simulation Parameters

Parameters	Values
Number of targets T_{Nm} (EA)	10000
Scope of target generation $\left(\left(LAT_1, LON_1\right) \sim \left(LAT_2, LON_2\right)\right)$	(0.4, 0.0) ∽ (1.2, 1.4)
Number of weapon groups B_{Nm} (EA)	100
Scope of weapon group generation $\left(\left(LAT_1, LON_1\right) \sim \left(LAT_2, LON_2\right)\right)$	(0.0, 0.0) ∽ (0.2, 0.7)
Number of available weapons per weapon group L_{g_b} (EA)	T_{Nm} / B_{Nm}
Number of protected assets A_{Nm} (EA)	100
Scope of protected asset generation $\left(\left(LAT_1, LON_1\right) \sim \left(LAT_2, LON_2\right)\right)$	(0.0, 0.0) ∽ (0.2, 1.4)
Weighted value representing the importance of weapons and protected assets w_p	$0 \le w_p \le 1$
Distribution form of targets, weapon groups and protected assets	Uniform distribution

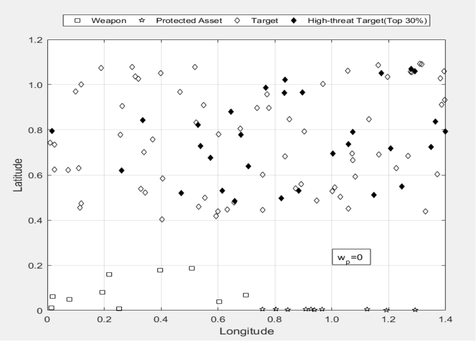
Fig. 3 represents the distribution of high-threat targets consequent on the location and weighted value of weapons and protected assets. Targets, weapon group and protected assets follow uniform distribution, and Fig. 3 is the case aiming at maximizing survival probability of protected assets, representing the weighted value of protected assets as 1($w_p = 0$).

(a) is the case where location creation scope of weapons and protected assets are not overlapped(weapon creation scope: (0.0, 0.0) ∽ (0.2, 0.7), protected assets creation scope: (0.0, 0.7) ∽ (0.2, 1.4)), and it's possible to identify that the distribution of high-threat targets of the top 30% threat level becomes different according to the weighted value w_p representing the importance of weapons and protected assets. In (a), the distribution of weapons leans toward the left while the distribution of protected assets leans towards the right, so it's possible to identify that when the weighted value($w_p = 0$) of protected assets is 1, high-threat targets are widely distributed on the right in contiguity with protected assets, whereas in case the weighted value of weapons is 1($w_p = 1$), high-threat targets are widely distributed on the left in contiguity with weapons.

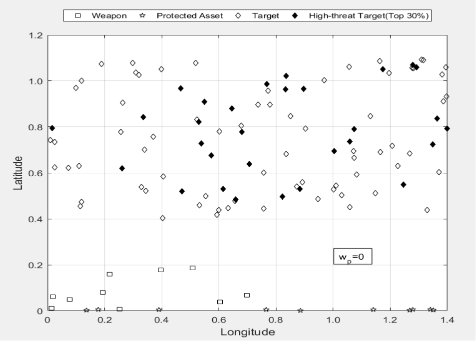
(b) is the case where the location creation scope of weapons and protected assets are overlapped only in part(weapon creation scope: (0.0, 0.0) ∽ (0.2, 0.7), protected assets creation scope: (0.0, 0.0) ∽(0.2, 1.4)), it has a characteristic that the location creation scope of protected assets is much wider than the location creation scope of weapons. In this case, it's possible to identify that when the weighted value of protected assets is 1($w_p = 0$), high-threat targets are evenly distributed on the whole, whereas in case the weighted value of weapons is 1($w_p = 1$), high-threat targets are widely distributed on the left in proximity to weapons.

(c) is the case where the location creation scopes of weapons and protected assets are overlapped(weapon creation scope: (0.0, 0.0) ∽ (0.2, 0.7), protected assets creation scope: (0.0, 0.0) ∽ (0.2, 0.7)), the location creation scopes of weapons and protected assets have the same characteristic. In other word, it's possible to identify that high-threat target distribution is the same when the weighted value of protected assets is 1($w_p = 0$), and when the weighted value of weapons is 1($w_p = 1$).

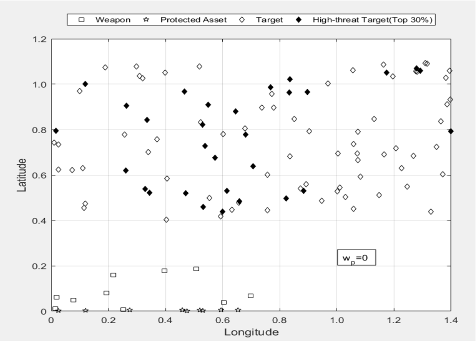
Through the analysis of the results of (a)~(c), it's possible to identify that the threat evaluation was effectively performed according to the weighted value w_p representing the importance of weapons and protected assets in the environment where the location of weapons and protected assets is diverse.



(a) The case where location creation scope of weapons and protected assets are not overlapped



(b) The case where location creation scope of weapons and protected assets are overlapped only in part



(c) The case where location creation scopes of weapons and protected assets are overlapped

Fig. 3. Distribution of high-threat targets consequent on the location and weighted value of weapons and protected assets

Fig. 4 represents the threat value consequent on the proximity degree and weighted value of targets. The proposed algorithm can identify that the smaller the proximity degree of targets, and the bigger the target weighted value w_t, the bigger the threat level E_t of targets, which aspects are analyzed to be attributable to the fact that the more adjacent to weapons or protected assets the targets are, the higher the weighted value according to target type, the higher the threat level. This paper proves that the proposed algorithm carries out threat evaluation for multiple ground targets specialized in the ground weapon system development environment by considering the characteristics of ground targets.

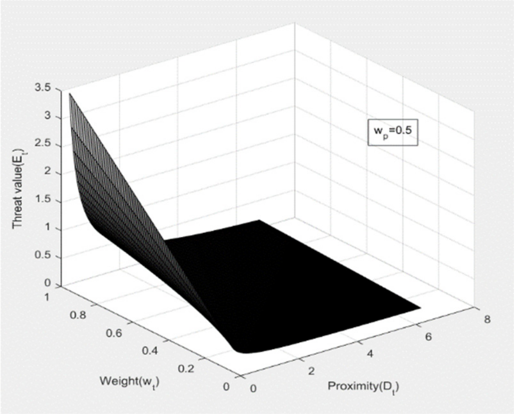


Fig. 4. Threat value consequent on the proximity degree and weighted value of targets

6. CONCLUSIONS

This paper proposed the threat evaluation algorithm for multiple ground targets in multi-target and multi-weapon environments. In case of the existing threat evaluation techniques, they are involved in the threat level evaluation method targeting anti-aircraft and anti-ship targets only, so there is a limit in applying them to ground weapon system development. Accordingly, this paper proposed the novel threat evaluation method optimized to multiple ground targets in the light of unique features of ground targets such as proximity degree, sorts of weapons and protected assets, target types, and relative importance of weapons and protected assets, etc. This way, it is possible to maximize an engagement effect by deducing an effective threat evaluation by taking into account the characteristics of ground targets comprehensively through the proposed algorithm. The proposed algorithm carried out performance evaluation and verification through simulations and visualization, and confirmed high utility and effects. The purpose of the follow-up research is to confirm the utility and excellence through the actual application to weapon devices.

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