Simulation Research on Anti-Drone Effectiveness of Artillery Equipment

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ABSTRACT.

With the improvement of drone intelligence level and the development of cluster control technology, drones gradually play an important role in the war, and how to defend against drone attacks has also become an important topic of close-range defence. This paper analyses the combat scenario of artillery strikes against drone targets, and according to the vulnerability characteristics of drone targets, takes the artillery equipment ammunition as the object, designs the effectiveness simulation process from hit to destruction, develops the effectiveness evaluation software, and carries out the simulation calculation. The simulation results show that artillery munitions have a high probability of causing damage to drone targets at close range, and increasing the distance of the anti-air proximity fuse appropriately can also increase the probability of artillery munitions causing damage to drones.

Keywords: anti-drone; artillery equipment; effectiveness evaluation

1. INTRODUCTION

With the improvement of the intelligence level of drones and the development of cluster control technology, drones are becoming cheaper and cheaper and their performance is getting stronger and stronger, and drone swarm warfare is also turning from concept to reality and from theory to practice. In the early hours of 14 September 2019, several drones attacked a Saudi oil company, paralysing two oil facilities at the world's largest crude oil purification plant and Saudi Arabia's second-largest oil field; on 3 January 2020, Iranian senior general Suleimani was "successfully decapitated" by U.S. forces using drones; and during the Russo-Ukrainian conflict, Ukraine used TB2 drones to sink the Russian warship Moscow in the Black Sea. In modern warfare, drones have achieved very impressive results. In order to cope with the increasingly significant threat of drones in future wars, countries are carrying out research on the destructive effects of different types of air defence weapons on drones, such as lasers[1], microwaves [2] and fixed-range bombs [3] .

In this paper, starting from the typical combat scenario of artillery anti-drone, combined with the hit and damage characteristics of artillery equipment and the vulnerability model of drones, we establish the simulation process of the damage effectiveness of artillery munitions against drones and carry out simulations to study the damage effectiveness of artillery munitions against drones under different artillery striking distances and fuzes' action distances.

2. SCENARIO ANALYSIS OF ARTILLERY-ARMED ANTI-UNMANNED CLUSTER OPERATIONS

2.1 Typical combat scenarios

The anti-drone technology is divided according to the means of combat and combat radius, and air defence weapons at different combat distances are obtained, as shown in Figure 1. Among them, high-velocity weapons, such as close-in cannons, have a close defensive distance and are difficult to defend against multiple drones at the same time; and although long-range anti-aircraft defence weapons such as anti-aircraft missiles have the advantages of high single-shot power, long anti-aircraft distance and high hit accuracy, the cost of single-shot munitions is relatively high, and the cost-efficiency ratio of anti-drone combat is very low.

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Air-to-air artillery munitions are characterised by high precision at close range, low cost and the ability to fire multiple rounds in succession to form a wide area of fragmentation, and are therefore capable of undertaking anti-drone combat tasks at close ranges of 2 to 5km.

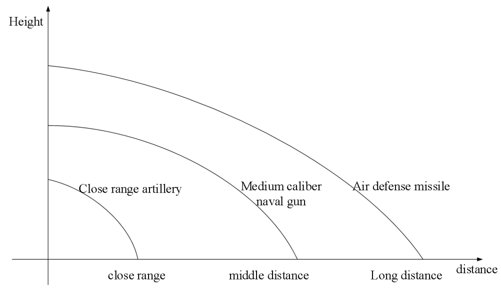


Figure 1. Operational range of air defence with different weaponry.

2.2 Anti-air artillery munition characteristics and simulation modelling

The hitting accuracy of anti-air artillery munitions is characterised by the density of standing targets at a certain distance. Standing target density refers to a group of projectiles on a certain target distance of the standing target shooting, the impact point relative to the average impact point of the degree of density or dispersion, it is a measure of the effectiveness of the weapon system on the target shooting one of the main characteristics of the parameter[4] . The mathematical characterisation of the denseness of the standing target is the denseness at a certain distance Lkm Ex, Ey.

Artillery anti-air munitions use an anti-air proximity fuse. The anti-air near-bombing fuse can detect a certain angle range of the target, when the target enters the detection area, the fuse starts to act, detonating the combat part. The mathematical characterisation of the detection area of the NEFF uses the detection distance L, the detection angle A1, A2 to jointly characterise, as shown in Figure 2.

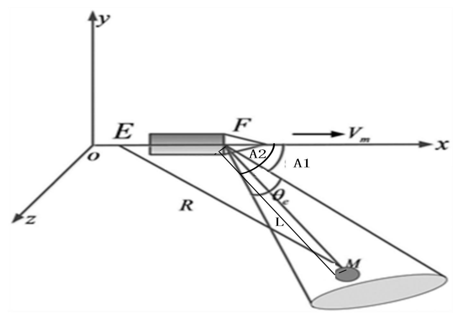


Figure 2. Schematic of anti-air proximity fuse detection area.

In order to ensure the density and dispersion direction of the fragments, the artillery anti-air munitions generally use prefabricated fragmentation combat sections, the distribution of the initial velocity of the prefabricated fragments along the shell, and the calculation of the initial velocity of the fragments[5] and the direction of dispersion[6] .

2.3 Drone Target Vulnerability Characteristics and Simulation Modelling

Due to the diversity of the battlefield environment and targets, and the different damage mechanisms and appearance characteristics, it is difficult to form a unified damage equivalence model. Therefore, the target system structure and function analysis is the basic link of target vulnerability, for a certain type of quadrotor unmanned aerial system, length 198mm, width 83mm, mass 0.75kg, flight speed 65km/h, endurance time 0.5 hours. Its main components include: propellers, motors, cameras, visual positioning system, antennas, batteries, paddle guards, open-source controllers, and ranging dot-matrix screen expansion modules. According to the functional characteristics of different components, it can be divided into the following five parts: visual positioning system, fuselage (structural system), battery (energy system), control system, motor and propeller (power system).

According to the analysis of the structure and function of the drone system, the equivalent modelling of the drone is carried out by 3D modelling software, and the equivalent simplified model of the drone is shown in Figure 3.

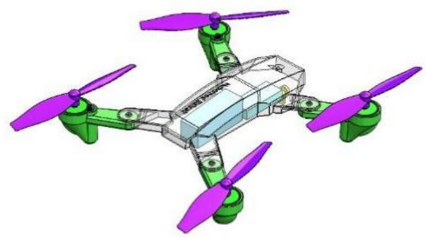


Figure 3. Drone structure.

For each system component, the effective number of fragments required for destruction is shown in Table 1.

Table 1. Criteria for the number of damaged fragments on structural parts of drone.

serial number	Part Name	Valid Fragmentation Criteria per piece
1	visual positioning system	1
2	fuselage	4
3	batteries	2
4	Motor and paddle system	1
5	Mission control module	2

The drone damage level and judgement conditions are shown in Table 2.[7]

Table 2. Conditions for determining the damage level of drones.

serial number	damage rating	Definition of damage	Key components	Physical damage characterisation
1	K	Complete loss of drone function	fuselage	Serious damage to fuselage
			batteries	Batteries are shot and burning
			control system	Control circuit board is shot
			aerofoil	Wing breaks or stops rotating
2	C	The drone was not able to fulfil its current intended	visual positioning system	Broken lens or damaged electronics

3. SIMULATION METHODS FOR DAMAGE EFFECTIVENESS

3.1 Calculation process

Since the drone fleet is an airborne cluster target with the characteristics of "low, small and slow", a typical move-to-move air combat, the model is more complex and has more factors influencing the damage effectiveness assessment model, therefore, reasonable assumptions must be made for the model in order to establish a reasonable, concise and practical damage effectiveness assessment model, therefore, the assumptions made are as follows:

(1) It is assumed that the trajectory of the prefabricated fragments after ejection from the battle section is straight, and that the flight rate and velocity decay law of each fragment are the same;

(2) The effect of rotation of the combat element and the prefabricated fragment around the centre of gravity in the air is negligible;

Based on the above assumptions, the simulation flow of the destruction efficacy of the designed artillery equipment against drone targets is shown in Figure4.

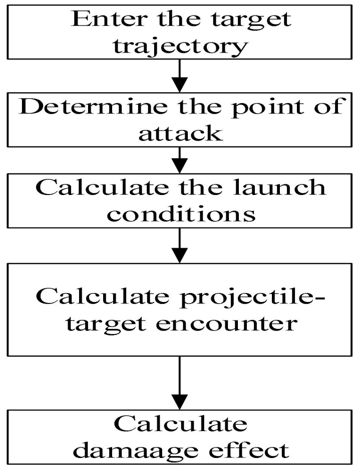


Figure 4. Simulation flow of artillery equipment's damage effectiveness against drone targets.

3.1.1 Calculation of the projectile rendezvous.

In the case of ballistic rendezvous calculations, it is necessary to describe the anti-aircraft trajectory and the target trajectory in the ground coordinate system, with the representation format (x,y,z,t). The origin O of the ground coordinate system and the projection of the air defence trajectory start point P on the ground coincide, the X-axis points to due east, the Z-axis points to due north, and the Y-axis is perpendicular to the ground and upwards.

Based on the artillery munition trajectory and air target trajectory, calculate the fuse detection area, when the target enters the fuse detection area, the munition detonation, calculate the relative position of the munition and the air target at this time, as shown in Figure 5.

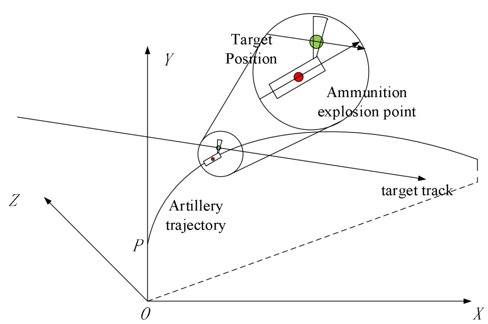


Figure 5. Schematic diagram of the calculation of projectile-ocular meeting.

3.1.2 Calculation of damage effectiveness.

When the artillery munition fires at the drone, based on the initial launch conditions, combined with the launch system error and munition error, sample the launch trajectory, combined with the target trajectory and fuzes, to determine whether the munition detonates or not; if the munition detonates, calculate the damage effect of the fragments of a single sample, if it does not detonate, the simulated artillery projectile fails to hit the target, and the damage effect is zero.

According to the formula[5] , calculate the residual speed of fragment penetration, calculate the kinetic energy of the fragment when destroying the equipment parts, and judge the result of destroying the parts by combining with the criterion of the number of destroying fragments of the structural parts of the drone.

According to the calculation results of the damage effect of each component of the target, get the damage result set K={k1 , k2 ,...,k14 } of each component; according to the damage result set K, find the damage set of the component corresponding to each damage level, and compare it to get the damage level of the drone of this sample; statistic the hitting situation and the damage level of all the sampled samples, and get the probability of the damage under the shooting condition.

3.2 Design of simulation software for damage effectiveness

The basic functions of the artillery munition anti-drone damage effectiveness simulation software are: ① calculate the detonation point of the anti-aircraft munition relative to the air target based on the air target trajectory and the terminal ballistic trajectory of the anti-aircraft munition, combined with the munition fuzing parameters; ② calculate the anti-aircraft munition's effectiveness in the air relative to the target's detonation point based on the anti-aircraft munition, combined with the anti-aircraft munition's fragmentation force field and the target susceptibility model. Based on the modular and loosely coupled design idea, the visual simulation software is designed into three modules, i.e., the module for the calculation of bullet-eye rendezvous, the module for the simulation of damage effectiveness and the module for the three-dimensional display. The system structure is shown in Figure 6.

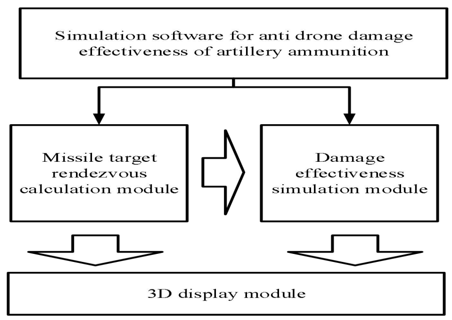


Figure 6. Artillery munitions anti-drone damage simulation software module architecture.

According to the target trajectory information and artillery ballistic trajectory, the bombing point coordinates of artillery munition striking drones are calculated by the projectile-eye rendezvous calculation module and transmitted to the damage effectiveness simulation module; according to the but-for bombing point, the damage effectiveness simulation module calculates the damage effectiveness of the target by combining with the target vulnerability model and the munition power model; according to the calculation results, the 3D display module carries out a three-dimensional visual display of the projectile-eye rendezvous situation and the damage effectiveness simulation results.

3.3 Simulation Example

3.3.1 Simulation of working conditions

Taking the drone as a target, the damage effectiveness of medium-calibre naval artillery munitions on this type of drone was calculated. The drone is set to fly in a straight line at a fixed altitude and at a constant speed, and the artillery munitions attack the drone from below in a straight line, as shown in the Figure below, to carry out the simulation of damage effectiveness.

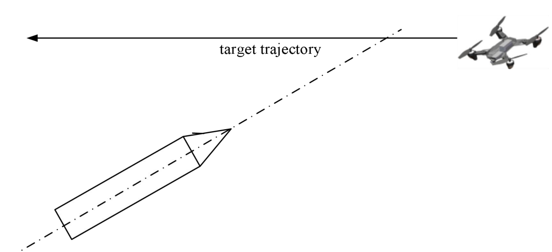
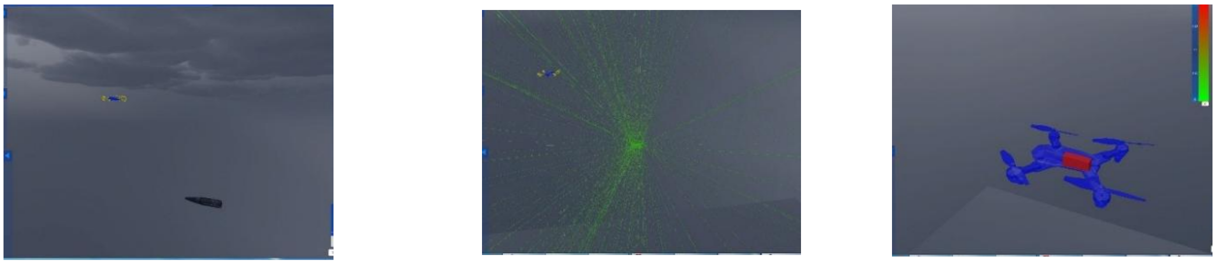


Figure 7. Schematic diagram of simulation working condition.

3.3.2 Simulation results and analyses

Using the performance simulation software, set the initial conditions for simulation according to the simulation conditions and carry out the simulation. The results of the damage effectiveness simulation are shown in Figure 8.



(a) (b) (c)

Figure 8. Simulation results of target damage effectiveness.

From the simulation results, it can be seen that after the artillery munition fuse detects the drone target, the explosion produces a conical shaped fragmentation killing area, the drone is in the fragmentation killing area, and the control system and battery of the drone are hit by the shrapnel and caused damage, resulting in the overall destruction of the drone.

4. ANALYSIS OF FACTORS AFFECTING DAMAGE EFFECTIVENESS

Based on the simulation example in Section 3.3, the simulation inputs were changed to investigate the effects of firing distance and munition fuse detonation distance on anti-drone damage effectiveness.

4.1 Simulation of the effect of firing range on damage effectiveness

The shooting distance is directly related to the hitting accuracy of the munition. The range of shooting distance is set to 2km~8km, and the step length is 0.5km, and the results are shown in Figure.9.

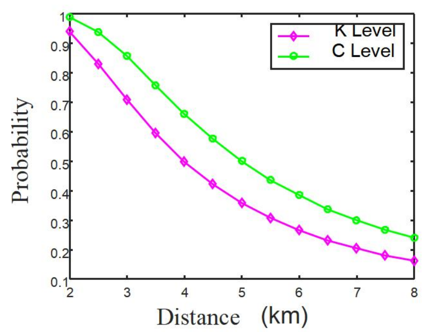


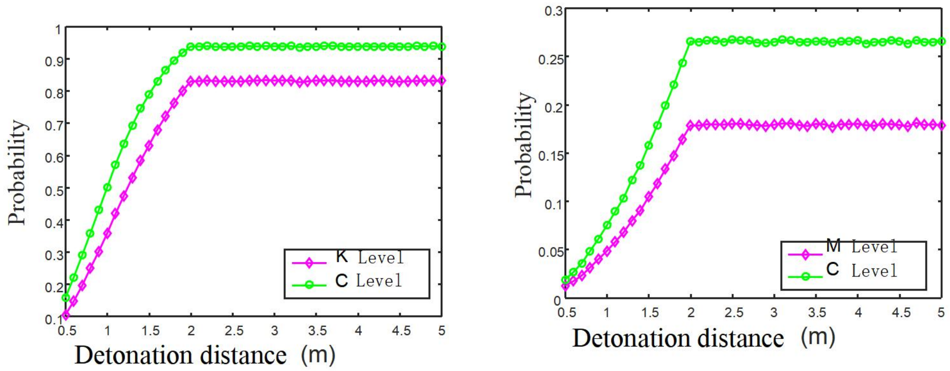
Figure 9. Simulation results of the effect of firing distance on the probability of destruction.

From the simulation results, it can be seen that artillery munitions have a probability of more than 50 per cent of causing K-level damage to the drone target and more than 67 per cent of causing C-level damage to the drone target within the range of 2-4 km; after the distance is greater than 5 km, the hitting accuracy of artillery munitions decreases, and the probability of artillery munitions damaging the drone decreases, with the probability of damaging the drone with a K-level or higher damage being only 38 per cent. Therefore, the optimal striking distance for artillery munitions against drones is between 2 and 5 kilometres.

4.2 Simulation of the effect of fuse detonation distance on destructive effect.

Set the fuse detonation distance calculation range of 0.5 ~ 5m, the calculation of the step length of 0.1m, divided into two cases of close-range shooting and long-range shooting to carry out simulation calculations of the destruction of the efficacy.

When the shooting distance is closer, the air hit accuracy is higher, different detonation distance under the destruction of the effectiveness of the simulation results in Figure.10 (a). When the shooting distance is farther away, the air hit accuracy is lower, different detonation distance under the destruction of the effectiveness of the simulation results as shown in Figure.10 (b).



(a) (b)

Figure 10. Schematic characterisation of the anti-drone damage radius of artillery munitions.

According to the Figure, it can be seen that the probability of K-class damage and the probability of C-class damage of drone targets are positively correlated with the fuze action distance within a certain range, and after reaching a certain value, increasing the fuze action distance will no longer increase the probability of damage of artillery munitions to drone targets.

5. CONCLUSION

This paper analyses the combat scenario of artillery strikes against drone targets, and according to the vulnerability of drone targets, takes the artillery equipment and ammunition as the object, designs the effectiveness simulation process and carries out the simulation calculations by integrating the whole process from hitting to destroying, and analyses the simulation results to get the following conclusions:

(1) Artillery munitions have a high probability of causing damage to drone targets at close range, with an optimal range of 2-5km and a K-level probability of damage of 50 per cent or more;

(2) Appropriately increasing the range of action of anti-air proximity fuzes can increase the probability of destruction of drones by artillery munitions.

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