Mechatronics and Automation Technology
J.-Y. Xu (Ed.)

doi:10.3233/ATDE231103

Discussion on the Intelligent Tactical Decision Aids of Shipborne Laser Weapons

Pengfei LIU[a,b,1], Shiyan SUN[a] and Jiaowei SHI[a]
[a] *Department of Weaponry Engineering, Naval University of Engineering, Wuhan 430033, Hubei, China*
[b] *China Coast Guard Academy, Ningbo 315801, Zhejiang, China*

Abstract. Laser weapons are sensitive to target and environment, of which tactical decision aids is complex and amount of calculation. The deep learning mechanism of weapon command, use and operation are established , which contribute to forming the intelligent assistant decision-making ability of laser weapon operational use. Both of them are the key to solve the problems about laser weapon of operation and use. They are also the means to promote the laser weapons of technicalization and real combat. The authors proposed preliminary conception of intelligent assist decision making based on multi-source data, case-based reasoning, nonlinear logic in the paper.

Keywords. Laser weapon; Tactical decision aids; Artificial intelligence.

1. Introduction

In general, tactical decision aids refers to the process of assisting and supporting decision makers to make decisions in the command and control system by means of tools and methods other than those of decision makers, which are generally computer-based models, algorithms, systems, etc., using scientific decision-making methods [1-3]. Tactical decision aids include operational command decision-making and weapon control decision-making. Operational command decision-making includes threat assessment, target allocation, fire channel organization, target indication, etc. [4]. Weapon control decision-making includes firing effectiveness estimation, timing judgment of firing, fire transfer and ceasefire, and tactical handling. The tactical decision aids for laser weapons refer to the process of fully automatically carrying out target threat assessment, target allocation, fire channel organization, fire efficiency estimation, tactical handling, and timing judgment of firing, fire transfer and ceasefire during the combat use of laser weapon systems.

Due to the inherent suddenness of ship defense tasks, the incompleteness and uncertainty of situational awareness, operators' reaction time is limitited to seconds or even sub-seconds [5]. In addition, the successful progress of the "kill chain" of laser

[1] Corresponding Author, Pengfei LIU, Department of weaponry engineering, Naval University of engineering, Wuhan, 430033, China; China Coast Guard Academy, Ningbo, 315801, China; E-mail: m15057445512@163.com.

weapons (as shown in figure 1) requires rapid fusion of various data, construction and evaluation of numerous options, prediction of combat capabilities, and handling of uncertainties, all of which further reduce the reaction time of the operators [6]. Laser weapon system operators must weigh many factors under dynamic threat conditions to choose between soft and hard kill options, select an effective aiming point for the target, calculate the required laser power in the barrel (actual laser irradiance in the target unit area), and calculate the required dwell time. In addition, operators must consider environmental factors, such as whether there is enough laser power to support the combat mission and real-time judgment of whether the target has been damaged. Therefore, rapid estimation of laser weapon's ability indicators to hit the target and fast pre-judgment of target damage conditions can provide operators with quick assist decision-making to maximize the overcoming of decision-making errors and shorten decision-making delays. The ability to make quick judgments determines whether high-energy tactical laser weapons can be truly deployed in practical combat applications.

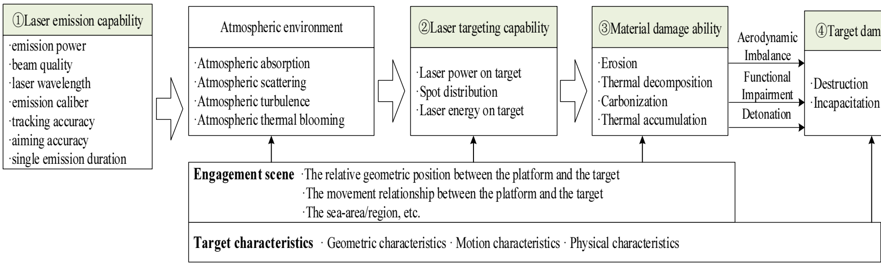

Figure 1. Laser Weapon's Kill Chain

The tactical decision aids methods should support the entire process of laser weapon combat use, including planning before firing, scheme formulation during firing, and online damage assessment. The pre-firing planning includes damage effect estimation, target allocation, etc., to solve the problem of whether the target can be engaged. Scheme formulation during firing includes timing of firing, selection of firing location, etc., to solve the problem of how to engage. Online damage assessment during firing solves the problems of timing for fire transfer and ceasefire. This article analyzes the differences between shipborne laser weapons and traditional kinetic defense weapons based on the complex logical relationship of "weapon-target-environment" and proposes a preliminary conception of intelligent tactical decision aids.

2. Similarities and Differences between Shipborne Laser Weapons and Traditional Kinetic Defense Weapons

The combat characteristics of weapons are the basis for studying decision support methods. By comparing and analyzing the combat characteristics of shipborne laser weapons and traditional kinetic defense weapons, we can learn from the commonalities and conduct specialized research on the differences.

2.1. Similarities

The similarities between SLAW and TKDW, include mission tasks, combat capabilities, modes of operation, and combat procedures. From the perspective of mission tasks, both laser weapons and short-range kinetic defense weapons can perform the tasks of close-range point-defense against targets such as missiles, bombs, manned/unmanned aircraft, etc. From the perspective of ability requirements, they both focus on firing accuracy, damage ability, react time, and range. From the perspective of operation mode, they can be divided into “fully automatic” and “human intervention” modes of operation. “Fully automatic” is the main mode, where after receiving target guidance, it is required to complete automatic target tracking, weapon alignment coordination, and firing tasks. From the perspective of combat procedures, in the “fully automatic” mode of operation, the system can automatically perform search detection of incoming targets, target recognition, track construction, threat assessment, target indication, fire channel organization, acquisition tracking, fire control calculation, firing effectiveness estimation, timing judgment of automatic firing, fire transfer, ceasefire, and tactical handling of the target.

2.2. Differences

Regarding the differences, we can analyze them from damage mode, fire methods, tracking and aiming methods, and weapon control methods. From the perspective of damage mode, traditional kinetic weapons cause hard damage to the target, while laser weapons can cause both hard and soft damage to the target. The damage principle of traditional kinetic weapons is based on the discrete accumulation of hits, fragments, and shockwaves, while laser weapons achieve continuous accumulation of energy on the target’s surface. In addition, there is also a significant difference in the function description of damage probability. The damage probability of traditional weapons is the product of the hit probability and the damage probability, while the damage probability of laser weapons is the integral of the product of the to-target energy probability density function and the target damage energy probability density function [7]. From the perspective of firing methods, traditional weapons and laser weapons differ in probabilistic firing and precise firing. Kinetic weapons such as artillery have a full-system firing accuracy in the milliradian range, far-field dispersion reaching several to tens of meters. Therefore, they adopt probabilistic strikes against targets as point targets. Laser weapons have a beam divergence angle in the micro-radian range, a far-field beam radius of only centimeters, and tracking accuracy in the micro-radian range. Therefore, laser weapons treat targets as area targets and select points for precise strikes on vulnerable parts. From the perspective of tracking and aiming methods, traditional kinetic weapons adopt a two-level tracking method of “target search detection + acquisition tracking”, while laser weapons adopt a three-level tracking method of “target search detection + coarse tracking + fine tracking” [8]. From the perspective of weapon control methods, traditional kinetic weapons aim at the target’s future position, while laser weapons aim at the target’s current position. Although the tactical application of laser weapons does not involve the problem of controlling kinetic weapons, such as track and solution hit, there are still issues to consider, such as selecting the aiming point and compensating for atmospheric transmission. Based on the characteristics of shipborne laser weapons, the research on tactical decision aids for shipborne laser weapons requires targeted studies.

3. Content of Shipborne Laser Weapon Intelligent Tactical Decision Aids Research

Laser weapon systems have not been tested in actual combat, nor are there any reference research materials from abroad. Compared with traditional kinetic weapons, laser weapons have undergone many changes in firing methods, fire direction, combat procedure, etc. The research content can be mainly divided into the following four parts.

Firstly, pre-firing planning. The core of fire channel organization and target allocation is damage effect prediction. In estimating the destruction effects, factors to be considered include the target's high-speed maneuvering, which causes rapid fluctuations in atmospheric transmission channels, resulting in intermittent visibility and jitter of target strike areas, as well as significant variations in vulnerability among different strike areas. Additionally, it is necessary to consider conflict resolution and safe launch when using high-power lasers in conjunction with cooperative platforms/weapons. Compared to traditional kinetic weapons, the demand for target indication precision has increased by three orders of magnitude, which is more complex when dealing with cluster targets.

Secondly, firing program formulation. The optimal firing timing, selection of strike locations, length of firing duration, and control of target attitudes/random jitters, atmospheric attenuation/scintillation on the firing channel are closely related in time and space. The formulation of firing programs for laser weapons is more precise and complex compared to traditional kinetic weapons, with an increase in the amount of calculations by two orders of magnitude.

Thirdly, online assessment of fire effects. Laser weapons generally do not directly cause target disintegration, incineration, or explosion, and the damage effects are not immediately evident. In most cases, indirect judgments are made based on variations in target motion, physical damage on the surface, and radiation spectra of optical images. Information for judging the damage is incomplete, ambiguous, and highly random. Furthermore, rapid automatic decision-making for countering multi-batch targets is required. So compared with traditional kinetic weapons, the timing of fire transfer and ceasefire judgment becomes more difficult [9].

Fourthly, the framework of tactical decision aids. Laser weapons are extremely sensitive to target, environmental, and scene changes, and the logical relationship of "weapon-target-environment" is very complex. Traditional kinetic defense weapons, such as short-range defense artillery, use a linear control mode, which has a large amount of calculations and low efficiency. To solve this problem, methods based on artificial intelligence such as deep learning [10,11], case reasoning [12], and fuzzy decision-making [13] can be viable solutions. However, there are no successful case studies to refer to for the decision support frameworks based on these methods in the field of laser weapon combat at present.

4. Main Methods of Shipborne Weapon Intelligent Tactical Decision Aids

4.1. Shipborne Guns' Tactical Decision Aids Methods

The fire theory of shipborne guns includes firing methods, fire direction (decision support) models, solving for firing data models, fire correction models, etc. The fire theory of traditional air defense artillery weapons includes the Artillery firing Theory of the Army, the Air Force Air Defense Antiaircraft Artillery firing Theory, and the Naval Ship Gun Air Combat Use Theory. The navy has accumulated solid research foundations in the use of shipborne laser weapons in short-range defense against air targets. Among them, firing methods usually include tracking firing, interception firing, and future airspace firing. The navy's shipborne guns usually use tracking firing and interception firing. Shipborne gun weapon systems mainly rely on tracking firing and direct destruction impact mechanisms, which are suitable for weapon systems with relatively high precision, fast response, and strong damage capabilities. When necessary, warning firing and interception firing can also be adopted. The Air Force's air defense artillery system has used the theory of "future airspace firing" to meet the needs of anti-aircraft artillery positions. The tactical-level laser weapons require continuous energy accumulation, and they usually adopt the tracking firing method. In this framework, the decision support models for traditional kinetic weapons, such as fire direction models, solving for firing data models, and firing correction models, can be used as references, but some of them need specialized research.

The mission tasks of shipborne gun weapon systems are generally to intercept 1-2 batches of air targets. The following principles are adopted: firstly, determine the target type based on the target's altitude and speed; determine the engagement range based on the target type and speed; determine the firing distance based on the engagement range. Secondly, perform firing effectiveness estimation. The firing effectiveness estimation is determined based on factors such as the engagement range, the number of consecutive shots, the target's motion parameters, and the system's firing error. Thirdly, determine the timing of fire transfer and ceasefire based on the online damage assessment. The damage evaluation is based on the target's attitude information and damage probability. In general, the traditional fire direction auxiliary decision-making model is based on two aspects. In terms of logic, it relies on simple judgment rules derived from experience. In terms of methodology, it is based on the probability-based analysis theory of weapon firing effectiveness.

There are many similarities between Laser weapon and short-range defense kinetic energy weapons in the operational link. Among them, the existing theoretical achievements can be directly used for reference in terms of tactical decision aids, such as threat judgment, target indication. The main method is based on the firing effectiveness analysis theory of Laser weapon, but many contents need special research according to the characteristics of Laser weapon. As shown in the table 1.

Table 1. Collection of Laser Weapon Tactical Decision Aids Algorithms.

Combat command procedure	Short-range Defensive Kinetic Weapons(using naval artillery as an example)	Laser Weapons
Information Proccession	search detection models track processing models target recognition models	☆search detection models ☆track processing models ☆target recognition models
Fire Direction Decision Aids	**threat decision models** **target indication models** **fire channel organization models** **damage ability estimation models** **timing judgment of firing models** **timing judgment of fire transfer and ceasefire models**	**☆threat decision models** **☆target indication models** **√fire channel organization models** **√damage ability estimation models** **√timing judgment of firing models** **√timing judgment of fire transfer and ceasefire models**

Target Tracking	target acquisition models target tracking models	√target acquisition models √target tracking models
Weapon Control	solving for firing data models firing correction models	**√automatic extraction of the damage point models** √solving for firing data models √firing correction models
Note：☆can be used as a reference；√ requires dedicated research; **The bold ones are tactical decision aids models.**		

4.2. Shipborne Laser Weapons' Intelligent Tactical Decision Aids

In 2021, Jane's Defense Weekly website reported that engineers at the Naval Surface Warfare Center Dahlgren Division (NSWCDD) in the United States developed an "Artificial Intelligence-based High Energy Laser Weapon Fire Control Decision Support System" to assist soldiers in improving response time and accuracy for operating high-energy laser weapons. According to reports on the website of the Naval Postgraduate School, the concept of "Cognitive Laser" was proposed, which combines laser weapon technology with artificial intelligence [14]. In response to "Cognitive Laser," a conceptual design for an automated decision support system was developed to support naval shipborne laser weapon combat decision-making.

The "Cognitive Laser" concept holds that "the laser weapon system and its use in naval ship defense provide a complex decision space for human tactical operators. They must be assisted by artificial intelligence to process, fuse, and understand a large amount of data and information within a short time frame and propose and evaluate effective action plans for complex systems, including laser weapons". The concept of "Cognitive Laser" believes that automation, artificial intelligence, and machine learning can provide cognitive solutions for human-machine collaboration, as shown in figure 2.

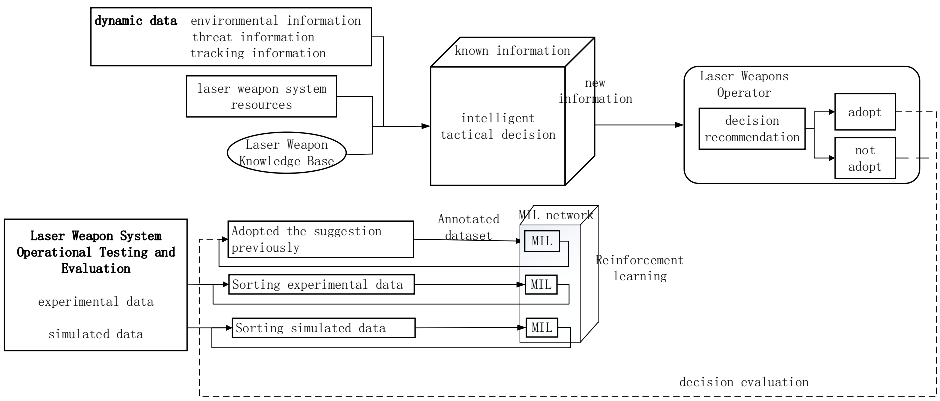

Figure 2. Machine learning for cognitive laser.

Regarding intelligent tactical decision aids, the hardware technology conditions are already available, but software frameworks and algorithms are in the exploration stage. The US military has developed a whole-ship computing environment in the DDG1000 destroyer, which features "cloud computing" technology. The whole-ship computing environment serves as a public information infrastructure for the combat system and will be promoted and applied in new main battle ships such as Ford-class aircraft carriers and littoral combat ships. In addition, the multi-platform collaborative air defense information system achieves composite tracking and identification of air defense combat, target indication, and other functions through multi-platform sensor networking, data fusion processing, and real-time information distribution. This system provides fire control-level situational data for weapon coordination control and lays the information foundation for intelligent tactical decision aids. Existing air defense weapons, such as shipborne gun systems, have autonomous combat capabilities based on rules. According to the nine-level standard of military intelligence as adopted by the US military, rule-based combat capabilities are roughly equivalent to level 3 (the highest level). At the level of weapon systems, higher-level intelligent tactical decision aids are still in the exploration stage. The hot issues in research on intelligent tactical decision aids for laser weapons include case-driven intelligent decision-making frameworks, situational estimation based on multi-source feature extraction, mission assignment planning based on intelligent algorithms, and engagement rule inference based on knowledge/model libraries [15]. Common intelligent decision-making frameworks are shown in figure 3.

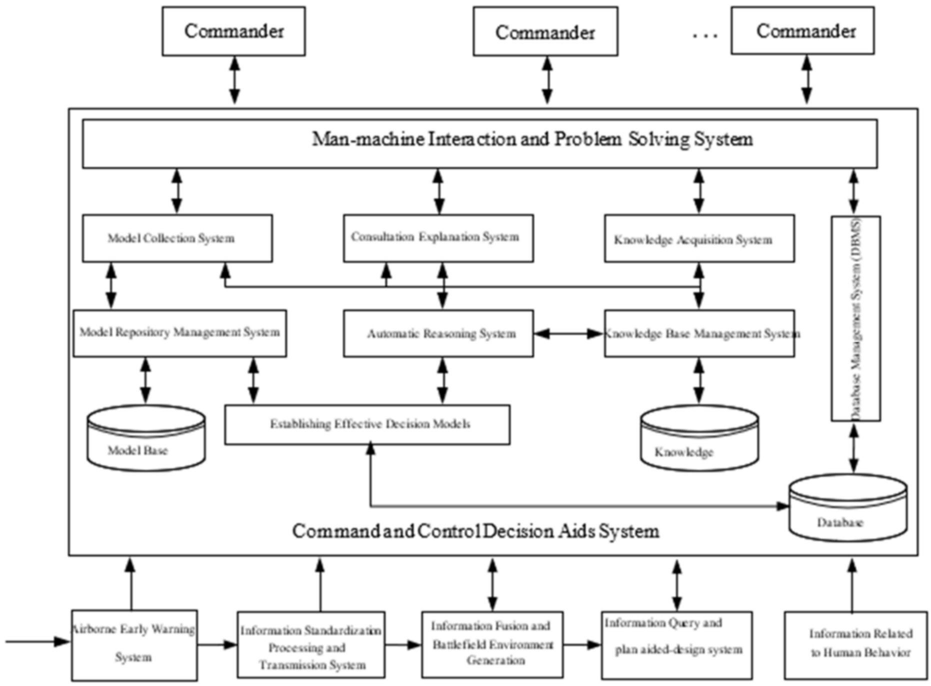

Figure 3. Common intelligent tactical decision aids.

5. Key Technical Issues in Shipborne Laser Weapon Intelligent Tactical Decision Aids

The first issue is online estimation of damage ability based on deep learning. Online estimation of laser weapon damage effectiveness [16] is the foundation of making combat decisions for laser weapons. In actual combat conditions, there are many factors that can affect the damage results of laser weapons against targets, including target type, track, vulnerability characteristics, atmospheric parameters, weapon system parameters, etc. However, weapon platform sensors have their limitations, and the information related to the target and the meteorology is not fully known. Therefore, it is necessary to quickly identify limited information, match and predict fuzzy parameters and algorithm models in the database, and then rapidly perform damage calculations and present the results to commanders.

The second issue is safe launch control based on conflict resolution. Launch safety control for laser weapons [17] is the basis for fully exerting combat capabilities. Most modern weapon installation platforms have relatively small spatial dimensions, and laser weapons may face “dangerous spaces” during launch when in close proximity to surrounding equipment facilities. There may also be potential crossfire issues with multi-weapon system firing zones, posing a significant threat to the safety of the weapon platform itself. When implementing laser weapon launch safety control, it is necessary to fully exert combat capabilities while avoiding firepower conflicts with other weapons and platforms, which is a problem that must be solved.

The third issue is cluster target assignment based on dynamic programming. Dealing with cluster targets is a typical combat scenario that laser weapons will face on the future battlefield. In actual combat operations, commanders use laser weapons to defend against unmanned clusters and other multiple targets and need to make command decisions under conditions of limited information and time constraints. Therefore, it is necessary to weigh known target threat levels, proximity, speed of approach, and consider the operating time and time for fire transfer of laser weapons to quickly formulate fire interception target sequences [18] in order to assist commanders in generating firing solutions for multiple targets within a limited time frame.

The forth issue is optimizing firing timing/aiming points based on effectiveness. Selecting the best firing timing and aiming points [19] is a critical concern for commanders. Laser weapons cause damage by continuously irradiating the target, but due to the target’s maneuverability and changes in the atmospheric environment, the required laser power during continuous irradiation can change. Thus, it is challenging to select the irradiation sections and irradiation locations in order to stabilize the power density at the target and increase the probability of component damage. Therefore, it is necessary to analyze the target’s flight track, predict the to-target power at different irradiation sections, obtain the to-target curve of laser weapons against the target, and analyze the vulnerability characteristics of the target to select the optimal interception sections and irradiation locations.

The fifth issue is automatic extraction of the damage point based on template matching. Currently, damage points are mainly extracted through manual selection, which is time-consuming [20]. To shorten the time, an automated extraction method based on template matching can be adopted. Automatic extraction of damage points requires prior information on different target vulnerabilities. Therefore, laser weapons must store target information and call relevant information during the selection process to obtain damage point information for different targets. After determining the damage point information, template matching methods are used to extract the specific coordinates of the damage points in the images. Based on the relationship between the image coordinates and the aiming points of the laser weapon, the deflection of the beam director and the aiming can be achieved. An automatic damage point extraction method helps to improve operational efficiency and optimize the effects of attacking targets.

The sixth issue is multi-source online assessment of damage effects. Judging whether the current target is damaged is an important prerequisite for laser weapons to perform fire transfer or ceasefire [21]. There are many detection methods for judging target damage in actual combat conditions. These include TV/infrared image information, radar information, and motion track information. However, due to the high-speed flight of targets, each detection method has certain limitations. Therefore, it is necessary to make comprehensive judgments on target dynamic damage based on multi-source fused information and combine prior knowledge.

The seventh issue is fast decision support based on case-driven methods. In the emergency conditions of air defense operations, commanders and operators of laser systems often face incomplete and uncertain intelligence regarding incoming targets [22]. In order to make rapid decision support based on limited target, environmental, and weapon status information, it is necessary to compare the collected information with accumulated test/training/simulation cases, and use fast fuzzy matching and fuzzy inference algorithms to form a fast decision support method driven by cases.

6. Conclusion

Tactical decision aids for laser weapons are fundamental and core issues in the combat application of laser weapons. The purpose of the basic theories and methods of tactical decision aids for laser weapons is to reveal the basic laws of laser weapon fire capability and command principles and serve as the cornerstone for the entire “kill chain” process of laser weapons. Laser weapons are extremely sensitive to target, environment and scene. The logical relationship of “weapon-target-environment” is very complex. Traditional kinetic defense weapons adopt a linear control mode, which has a large amount of calculations and low efficiency. Deep learning, case reasoning, fuzzy decision-making, and other methods based on artificial intelligence are feasible solutions to realize intelligent tactical decision aids for laser weapons.

References

[1] Carroll D L. Past, Present, and Future of High-Energy Lasers [J]. High Power Laser Science and Engineering, 2012, 2.

[2] U.S. Congressional Research Service. Background and Issues for Naval Shipboard Lasers: Surface Warfare, Air Defense, and Ballistic Missile Defense [R], 2012.

[3] Center for Strategic and Budgetary Assessments. Changing the Rules of War: The Future of Directed Energy Weapons [R], 2012.

[4] Su, Y and Wan, M. High-Energy Laser Weapon Systems [M]. Beijing: National Defense Industry Press, 2004.

[5] Shipborne weapons are evolving towards high-energy weapons.

[6] Jhoson B. Cognitive Lasers: Combing Artificial Intelligence with Laser Weapon System [R], 2021.

[7] Nie Y -X. The US Navy has developed HEL FCDA[DB/OL].

[8] Tian X -G, Tian X -G and Zuo Q -W; et al. Research status and development trend of artificial intelligencetechnology in the field of combat assisted decision making [C]. The Proceedings of the 10th China Command and Control Conference, 2022: 438-445.

[9] Li B -X, Zhang F and Li Q -F, et al. Research on the Application of Artificial Intelligence Technology in Military Field [J]. Journal of China Academy of Electronics and Information Technology, 2022, 17 (03), 238-246.

[10] Zheng H -L, Chen T -J, Xu L, Cuo H -X and Yang Y. Discussion on Model Design and Evaluation Method of Assitant Combat Decision-Making [J]. Fire Control and Command Control, 2021, 46 (10): 67-72.

[11] Zhang X -H and Cao X -W. On Military Assistant Decision Based on Deep Learning [J]. Fire Control

and Command Control, 2020, 45 (03): 1-6.
[12] Tan Y -X, Fan R and Xiao, D. Research on Prediction Method of Army Equipment Support Requirement Based on Operation Simulation Case-Reasoning [J]. Journal of System Simulation, 2015, 27 (09): 2056-2065+2074.
[13] Xu C. Development and Military Applications of Computer Vision Technology in the United States [J]. Electronic Components and Information Technology, 2022, 6 (08): 8-12.
[14] Yang J -B, Zong S -G and Chen L -F. Research on destruction distance of shipborne laser weapon to typical UAV swarm target [J]. Laser and Infrared, 2022, 52 (05): 745-751.
[15] Xu C -R, Sun S -Y, She B and Zhou J -F. Research on Combat Effectiveness of Ten-Kilowatt Shipborne Laser Weapon Against UAV [J]. Journal of Ordnance Equipment Engineering, 2021, 42 (12): 129-134.
[16] Lu F -B, Cui D -H and Lin L -X, et al. Capability Analysis of Electro-optical Sensor of Laser Blinding Weapon [J]. Electro-Optic Technology Application, 2020, 35 (05): 34-37.
[17] Rao R Z. The Bumpy Course of Laser Weapon [J]. Science, 2020, 72 (05): 59-63+4.
[18] Ma B, Hou Z -Q, Jiao H -F, Zhang J -L, Shen Z -X, Chen X -B and Wang Z -S. Pulsed laser-induced damage threshold measurement and damage performance of optical components [J]. Optics and Precision Engineering, 2022, 30 (21): 2805-2826.
[19] Aobudukremu A, Ren Y -C, Tao Z -W, Liu S -W, Li Y -L and Rao R -Z. Influence of atmospheric turbulence on temporal coherence properties of received optical fields [J/OL]. Acta Physica Sinica, 2022, 28 (04): 1-17.
[20] Wang X -D, Xiang Q and Li R, et al. Review of Deep Learning Research and Application of New Scientific Discoveries to Military [J]. Journal of Air Fouce Engineering Universitu (Natural Science Edition), 2022, 23 (01): 1-11.
[21] Luo J, Sun G and Wang G -J. Pythagoras fuzzy decision-making method based on risk preference score function and Choquet integral operator [J/OL]. Fuzzy Systems and Mathematics, 2022, 4: 1-10.
[22] Luo L and Tan B -T. Research on operational application of shipborne laser weapon [J]. Laser and Infrared, 2022, 52 (07): 1058-1063.