Modeling the Impact of High Energy Laser Weapon on the Mission Effectiveness of Unmanned Combat Aerial Vehicles

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ABSTRACT With the rapid development of high energy laser weapons (HELWs), the integration of HELW on unmanned combat aerial vehicles (UCAVs) has become a hot research topic. To study the impact of HELW on UCAV mission effectiveness, this paper proposes a 4-level design framework based on the system-of-system (SoS) oriented design. To validate the framework, the impact of HELW is analyzed in four aspects: the strike capability, the stealth performance, the vulnerability, and the defense capability, where the UCAV design constrains are noted. Simulation experiments of penetration scenario are carried out using agent-based modeling and simulation. The simulation results show that the integration of HELW can increase the survivability and mission effectiveness rate (MER) of the UCAV, especially for UCAVs with high speed and stealth performance. But the MER of the UCAV does not increase with the increase of HELW output power in most cases, indicating the importance of balancing the HELW and UCAV performances in concept design.

INDEX TERMS High energy laser, unmanned combat aerial vehicle, system-of-systems oriented design, mission effectiveness evaluation, agent-based modeling and simulation.

I. INTRODUCTION

Unmanned combat aerial vehicles (UCAVs) are widely used in military surveillance, electronic interference, communication relay, and anti-surface strike missions due to low cost, high flexibility, and long endurance. The capability of remote control makes the UCAV particularly suitable for dangerous missions without worrying about the pilot casualty. But UCAVs are fragile in air defense system because of their low speed, limited maneuverability, and high vulnerability [1]. To obtain higher survivability and mission sustainability, the implementation of high energy laser weapon (HELW) could be a suitable option.

Comparing with conventional blast and fragment weapons, HELWs have significant advantages such as pinpoint accuracy, deep magazine, and instant engagement capability. Moreover, the clean air of high altitude and the thin armor of aerial targets make aircraft a better platform than surface vehicles [2]. But the integration of HELW on aircraft was never an easy task. As the most advanced country in laser technology, America has developed a serious of airborne laser

programs, such as Airborne Laser Laboratory (ALL), Airborne Laser (ABL), Advanced Tactical Laser (ATL), Aero-adaptive Aero-optic Beam Control (ABC), and High Energy Liquid Laser Area Defense System (HELLADS) [3], [4].

The integration of HELW into aircraft is extremely complex, especially for UCAVs having small size and stringent payload constrains. Many works have been done to evaluate the performance of HELW, including the influence evaluation of the airflow speed and laser spot size to material damage mechanism [6], the influence of weather to high energy laser propagation [7], the influence of altitude and propagation angle to the beam spreading and wander variance [8] as well as the influence evaluation of the observation error on killing time and laser facula area [9]. The lethality of laser weapon programs is also studied, Jan Stupl assessed the capability of ABL in defense against ballistic missiles with physics-based simulation models [5] that considering the attenuation of laser energy during propagation and the deposition of laser energy on the surface of the ballistic missile. Most of the previous works focus on the trade-off of laser weapon performance without considering the influence of platform performance to mission effectiveness. Antonios Lionis evaluated the UCAV parameters on the lethality of laser weapon [10] with a

laser propagation model. Parameters of UCAV speed, altitude, engage direction, endurance, platform jitter, and beam quality are analyzed. But like most of the previous works, the penalties of HELW to UCAV are not considered. However, to design a UCAV with HELW aboard, both the benefits and the penalties of the HELW should be considered.

Mission effectiveness evaluation is the basis of aircraft concept design. Traditional effectiveness evaluation methods such as index method [11], analytic hierarchy process (AHP) [12], and multidisciplinary design optimization (MDO) [13] lack the capability of considering the complexity of battlefield. SoS oriented design is a new method that emphasized mission effectiveness rather than subsystem performance [14]–[16]. Agent-based modelling and simulation (ABMS) is the main analysis method in SoS oriented mission effectiveness evaluation for its advantage of flexibility, modularity, and interactivity [17], [18]. It has been widely used to analyze the influence of aircraft performance to mission success rate [19], the combat aircraft contribution effectiveness [20], and the UAV swarm surveillance effectiveness [21]. But most of the previous works are doing subsystem performance trade-offs without considering the constrains of design parameters, the enhance of one parameter has no influence to other performance, which is not the real case.

In this paper, a SoS oriented mission effectiveness evaluation methodology that considers the interaction between HELW and UCAV is proposed based on the 2-level SoS framework in reference [21]. A bottom level is added for subsystem interaction analysis, thus the UCAV combat performance is constrained by HELW design parameters. The improved 4-level SoS oriented design framework can estimate the mission effectiveness reaction according to subsystem design parameters, instead of doing trade-offs at the technical level intuitively. Besides, a HELW power system model is presented so that the dynamic operation process of the subsystem can be analyzed.

The paper is organized as follows. The mission scenario and the mission effectiveness measurement are proposed in section II. The models for HELW engagement simulation are described in section III. A SoS orientated mission effectiveness evaluation framework is proposed in section IV, and the agent-based model architecture is built. The subsystem interaction model is proposed in section V. Finally, a simulation example is presented in section VI.

II. PROBLEM FORMULATION

A. MISSION SCENARIO

A SoS view of relationship between the subsystem design parameters and the mission effectiveness is established through a penetration mission scenario, as shown in Fig. 1. The fictive mission scenario illustrates a group of UCAVs penetrates across a hostile area to bomb the target guarded by air defense bases.

FIGURE 1. The penetration mission scenario.

The engage process is shown in Fig. 2. The air defense bases use radar to detect and launch missiles to intercept the UCAVs. At the beginning, the radar maneuvers the semi-active missile according to the target track information. As long as the UCAV is captured, the missile turns into the active guidance mode and calculates the target track. The UCAV can detect and rank the threat with the missile approach warning system, and lock the highest threat target by the electro-optical sensor. After identifying the approaching missile, the aboard HELW system will fire a laser beam which travels through the atmosphere to reach the missile and maintains a small laser spot on the surface until the destruction. If the missile is destroyed, the air defense base usually launches another missile as long as the UCAVs are still inside the range of fire. After the penetration of the air defense area, the surviving UCAVs can bomb the protected assets with mounted missiles. The implementation models involved in the engagement process are described in section III.

B. MEASURE OF MISSION EFFECTIVENESS

The HELW can increase the survivability of the UCAV by destroying the anti-air missiles actively. Because of the constant total payload of the UCAV, the mounted missiles are constrained by the weight of the HELW. Thus, the survivability and the strike capability of the UCAV are linked directly to the output power of the HELW. Hence, a mission effectiveness rate (MER) is used to measure the impact of the HELW to the SoS mission effectiveness. MER is defined as the ratio of the UCAV cost to the destroyed target value.

$$MER = \frac{C_{UK}}{C_{TK}} \qquad (1)$$

where $C_{UK} = n_{UK}C_{U0}$ represents the cost of the UCAV, n_{UK} is the number of UCAVs get killed, C_{U0} is the value of each UCAV. $C_{TK} = n_{Td}C_{T0}$ indicates the value of the destroyed targets, n_{Td} is the destroyed target number, C_{T0} is the value of each target. The value of each UCAV C_{U0} is influenced by the speed v_U and RCS σ_U of the UCAV and the output power
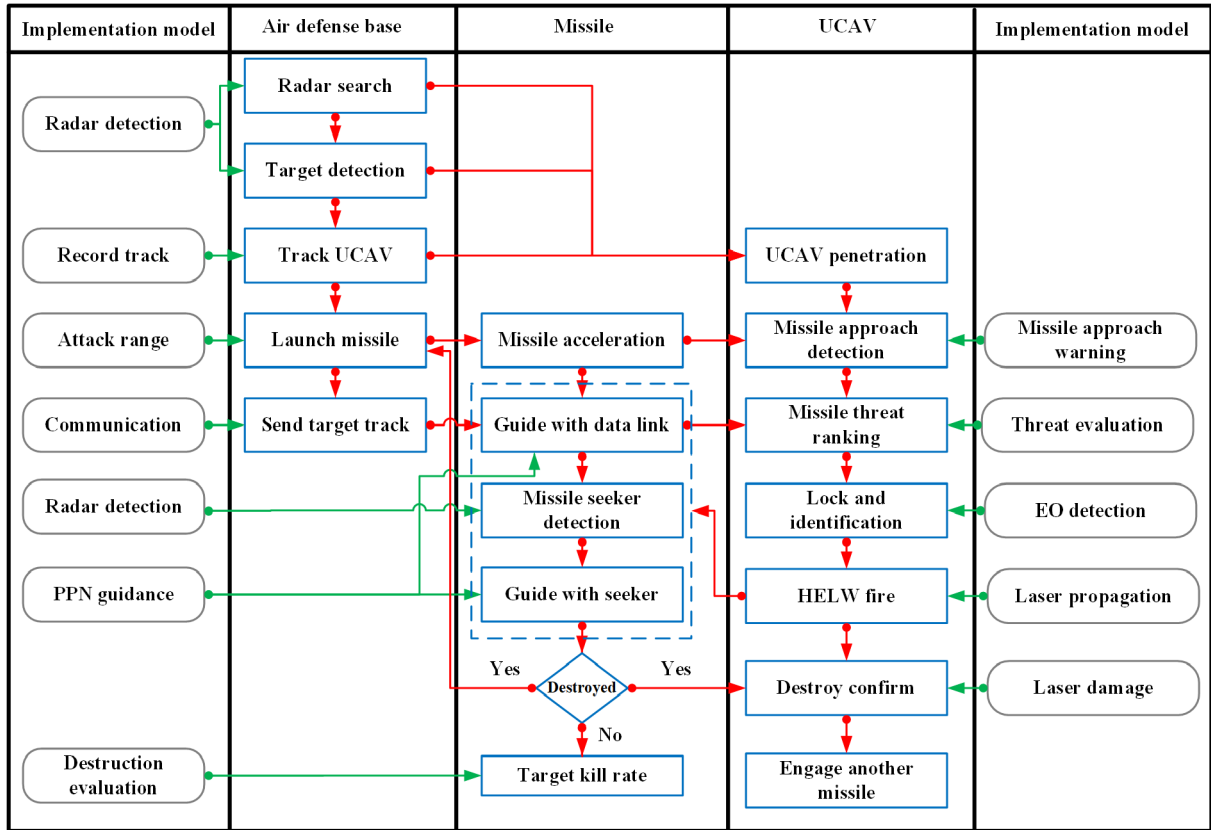
FIGURE 2. The engagement process and implementation models in penetration mission.

P_0 of the HELW

$$C_{U0} = \alpha_1 e^{\alpha_2 v_U} + \beta_1 e^{\beta_2 \sigma_U} + \gamma P_0 \qquad (2)$$

where α_1 and α_2 are the cost coefficients of the speed of the UCAV, β_1 and β_2 are the cost coefficients of the RCS of the UCAV, γ is the cost coefficient of the HELW output power.

III. IMPLEMENTATION MODELS

A. RADAR DETECTION MODEL
Both the enemy air defense base and the seeker of the surface-to-air missile use radar to detect targets. The radar generates a random Boolean event according to the detection probability P_D with a specific scanning frequency. The radar can switch to the track state with a high scanning frequency if it gets 3 success within 4 times of detection, and switch back to the search state with a low frequency if it gets 5 fails within 5 times of detection.

The radar detection probability of the air defense system is modeled with the widely used cell averaging constant false alarm rate (CACFAR) detection method, also named as the "adaptive threshold detection" [22]. It is expressed as,

$$P_D = \left[1 + \frac{\alpha_{CA}/N_R}{1 + SNR} \right]^{-N_R} \qquad (3)$$

where N_R represents neighboring cells number in the CFAR window, SNR indicates the signal to noise ratio. α_{CA} is the

threshold factor, and can be obtained by

$$\alpha_{CA} = N_R \left[P_{FA}^{-1/N_R} - 1 \right] \qquad (4)$$

where P_{FA} is the desired false alarm rate.

For a given radar detecting a target with an RCS of σ_0 at a range of R_0, the signal to noise ratio is SNR_0. Thus, to a target with a RCS of σ at range R, the signal to noise ratio can be obtained as,

$$SNR = \frac{R_0^4 \sigma}{\sigma_0 R^4} SNR_0 \qquad (5)$$

B. TRACK RECORD MODEL
The track of an agent is a series estimation of time-related location and velocity. The movement of the agent is modeled according the 3 degree-of-freedom kinetic equations in reference [23].

$$\begin{cases} \dot{x} = \dfrac{dx}{dt} = v \cos \gamma \cos \chi \\[4pt] \dot{y} = \dfrac{dy}{dt} = v \cos \gamma \sin \chi \\[4pt] \dot{z} = \dfrac{dz}{dt} = -v \sin \gamma \\[4pt] \dfrac{dv}{dt} = g \left(n_x - \sin \gamma \right) \\[4pt] v \cos \gamma \dfrac{d\chi}{dt} = g n_y \\[4pt] v \dfrac{d\gamma}{dt} = g \left(n_z - \cos \gamma \right) \end{cases} \qquad (6)$$

where (x, y, z) and $(\dot{x}, \dot{y}, \dot{z})$ are the position and velocity of the agent in three axes, v, γ, χ are the magnitude, pitch angle, and yaw angle of the agent velocity respectively. (n_x, n_y, n_z) is the overload of the agent. Thus, the movement of the agent is controlled by the overload. Different overload commands can make different motions.

The track of agent i at time t is recorded as

$$\hat{X}_i(t) = X_i(t) + \sigma_i(t) \tag{7}$$

where $X_i(t) = (x(t), y(t), z(t), \dot{x}(t), \dot{y}(t), \dot{z}(t))$ indicates the state of agent i at time t, $(x(t), y(t), z(t))$ and $(\dot{x}(t), \dot{y}(t), \dot{z}(t))$ are the position and velocity of the agent in three axes, respectively, $\sigma_i(t)$ is the estimate error of the agent [23]. The distance of targets can be calculated according to the target track, so that the launch command and threat list can be made.

C. ELECTRO-OPTICAL DETECTION MODEL

The HELW uses electro-optical sensor to detect and track targets. The detection process is divided into four phases. Firstly, assume the sensor is able to detect the missile as soon as they are launched with the missile approach warning system. So, the relative position and speed of the targets can be calculated. Secondly, the sensor evaluates the threat of the targets according to relative range and chooses the highest threat as its target. Thirdly, the sensor zooms in and calculates the detection, recognition, and identification probability of the target. Fourthly, if the target is in fire range, the HELW shoot a laser beam to destroy it and move on to the next target.

The horizontal and vertical field of view of the sensor θ_h and θ_v is

$$\theta_h = 2 \arctan\left(\frac{h_{\text{FPA}}}{2 f_c}\right) \tag{8}$$

$$\theta_v = 2 \arctan\left(\frac{v_{\text{FPA}}}{2 f_c}\right) \tag{9}$$

where f_c represents the focal length, h_{FPA} and v_{FPA} are the corresponding horizontal and vertical size of the sensor.

The probability of discrimination is measured with the Johnson Criteria [24]

$$p(N) = \frac{(N/N_{50})^{2.7+0.7(N/NS0)}}{1 + (N/N_{50})^{2.7+0.7(N/N50)}} \tag{10}$$

where N_{50} is the 50% success probability of performing a detection task, the value is 0.75, 3.0, and 6.0 for detection, recognition, and identification respectively. N is the number of cycles across the target

$$N = \frac{d_t f_c}{2 R r_{FPA}} \tag{11}$$

where d_t is the size of the target, R is the target range, r_{FPA} is the resolution of the sensor.

D. LASER BEAM PROPAGATION MODEL

While traveling a long distance in the atmosphere, the laser beam will experience a series of attenuation effects before reaching the target. The power density of the laser finally reached the target is

$$I = \frac{P_0 \tau_a}{\pi r^2} \tag{12}$$

where P_0 is the output power of the HELW, τ_a is the atmospheric transmission coefficient, r is the spot radius on the target.

the atmospheric transmission coefficient τ_a for slant path propagation can be obtained with empirical equation [25]

$$\tau_a = e^{-\sec(\theta)K/V_M[\exp(-0.835h_b)-\exp(-0.835h_a)]} \tag{13}$$

where θ is the zenith angle of the laser beam, K is a constant number based on the aerosol type, V_M is the atmospheric visibility, h_a and h_b are the altitude of the laser source and the target.

the spot radius r on the target is

$$r = R\left(\sigma_D^2 + \sigma_J^2 + \sigma_T^2\right)^{1/2}\left(1 + 0.0625N_D^2\right)^{1/2} \tag{14}$$

where λ is the laser beam wavelength, D is the output mirror diameter, R is the target range, σ_D, σ_J, and σ_T are the spread angle caused by diffraction, jitter, and turbulence. N_D is the thermal blooming distortion parameter. These distortion parameters can be obtained by [26]–[28]

$$\begin{cases} \sigma_D = 1.22\frac{\lambda}{D} \\ \sigma_T = \sqrt{0.182}\left(1.22\frac{\lambda}{D}\right)\left(\frac{\sqrt{2}D}{r_c}\right) \\ N_D = \dfrac{16\sqrt{2}\,(-n_T)\,\alpha P_0 R^2}{\pi n_0 \rho c_p v D^3} \end{cases} \tag{15}$$

$$\begin{cases} r_c = \left[1.46(2\pi/\lambda)^2 \int_{h_b}^{h_a} C_n^2(h)dh\right]^{-3/5} \\ C_n^2(h) = 8.148\times10^{-56}v^2 h^{10}e^{-h/1000} \\ \quad +2.7\times10^{-16}e^{-h/1500} + C_n^2(0)e^{-h/100} \end{cases} \tag{16}$$

where r_c is the atmospheric coherent length, n_0 is the atmospheric refractivity, n_T is the atmospheric reflectivity change rate, α is the atmospheric absorption parameter, ρ is the air density, c_p is the air heat capacity, v is the wind speed.

E. LASER DAMAGE MODEL

The damage mechanism of laser weapon is to heat the target with a beam of high-power energy. The shell of missile is designed to withstand the overload with minimum thickness to save weight for the fuel and explosive payload, which made the missile pretty fragile to laser weapon. The HELW doesn't need to literally melt the whole missile, it only needs to heat the shell to a specific temperature where the material will be too soft to withstand the aerodynamic stress, and the missile will break up by itself [6]. The temperature of the shell can be calculated as,

$$T = \int_{t_s}^{t_e} I(t)\frac{(1-r_f)}{c_{pm}\rho_m Sh_m}dt + T_0 \tag{17}$$

where c_{pm} and ρ_m are the heat capacity and density of the material, t_s and t_e are the start and end time of the engagement, S is unit area, h_m is the shell thickness, T_0 is the initial temperature, r_f is the surface reflectivity of the material, I is the power density of the laser spot, which is constantly changing during the engagement. The missile is considered to be destroyed when T reaches the damage threshold temperature.

F. MISSILE GUIDANCE MODEL

The missile movement is modeled according to the 3 degree-of-freedom kinetic equations shown in (6). The overload commands of the missile are calculated according to the missile guidance model.

The missile guidance model is the pure proportional navigation (PPN) method, the guidance law used by most missiles in operation today. The basic principle is that the velocity vector rotate rate of the missile should be directly proportional to the rotation rate of the line of sight [29]. The 3D acceleration command according to proportional navigation guidance law is

$$\boldsymbol{a} = N_g\boldsymbol{\omega} \times \boldsymbol{V}_m \tag{18}$$

where $\boldsymbol{a}$ represents the acceleration command, N_g is the proportional navigation coefficient, $\boldsymbol{V}_m$ is the missile speed vector, $\boldsymbol{\omega}$ is the rotation angular velocity of the line of sight.

$$\boldsymbol{\omega} = \frac{\boldsymbol{R}_r \times \boldsymbol{V}_r}{\boldsymbol{R}_r \cdot \boldsymbol{R}_r} \tag{19}$$

where $\boldsymbol{R}_r$ and $\boldsymbol{V}_r$ are the relative range vector and relative speed vector of the missile and the target. Thus, the overload of the agent can be calculated according to the acceleration command with coordinate transformation.

IV. PROPOSED APPROACH

A. SYSTEM-OF-SYSTEM ORIENTED APPROACH

As shown in Fig. 3, the design framework is divided into 4 levels and built from the bottom up. The laser output power is the main HELW variable, and the payload capacity and the power supply of the UCAV are chosen to be the main constrains, which are illustrated at the subsystem level shown in Fig. 3. In the technical level, the susceptibility and vulnerability of each UCAV and the attacking missile can be calculated through a series of technical models described in section 3. At the system level, the number of survived UCAVs and targets destroyed can be obtained through combat simulation. Finally, the SoS mission effectiveness can be obtained according to the effectiveness evaluation model. Thus, the output of the lower level becomes the input of the upper level. The subsystem design parameters at the bottom are linked to the top SoS level mission effectiveness through a serious of models.

The interaction of subsystem parameters mainly influences the UCAV performance in four aspects: the strike capability, the stealth performance, the vulnerability and the defense capability. First, the aboard of HELW will decrease the number of mounted missiles due to the limited load capacity of
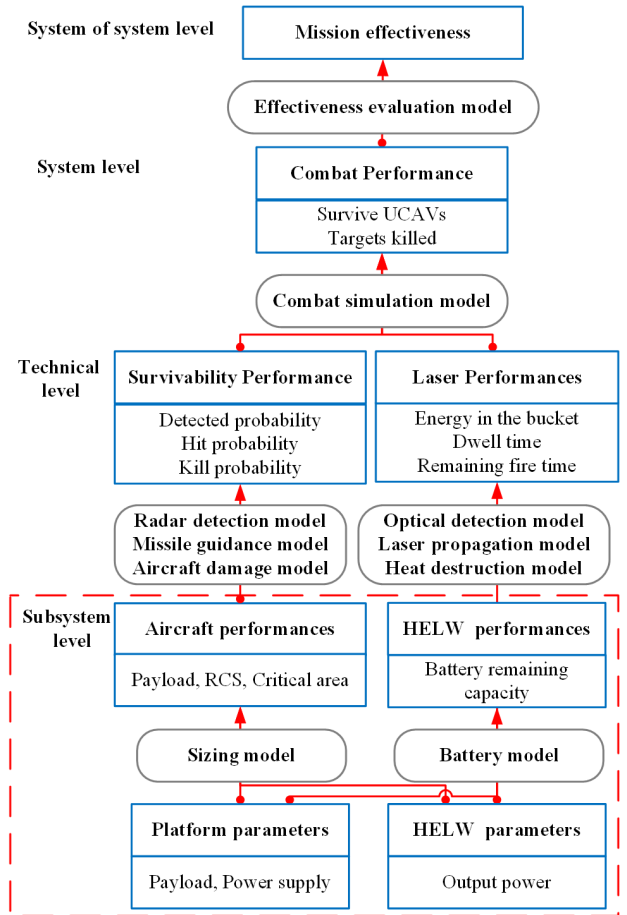
FIGURE 3. An illustration of the model framework to support the UCAV and HELW design.

the UCAV, and lead to a decrease of its strike capability. The missile number decreases with the increasement of HELW weight. Second, most UCAVs mount the missiles on the wing pylons or under the fuselage, which increases the radar cross section area (RCS) of the UCAV tremendously. The decrease of the missile number outside the aircraft can have a positive influence on the stealth performance of the UCAV. Third, the vulnerability of an aircraft depends on the size of critical area. The critical area of the UCAV decreases with the reduction of mounted missile number, so that the aboard of HELW could reduce the vulnerability of the UCAV. Fourth, generally, the battery can support HELW to fire for a short period of time and needs to recharge after each shot. But to a given UCAV, the maximum power supply of the aboard generator is constant. The power supply of the UCAV limits the sustainability of HELW. The electric power of the generator would not be sufficient to recharge the battery in time if the HELW output power is high or the enemy counterattack is intense.

B. AGENT-BASED ANALYSIS SCHEME

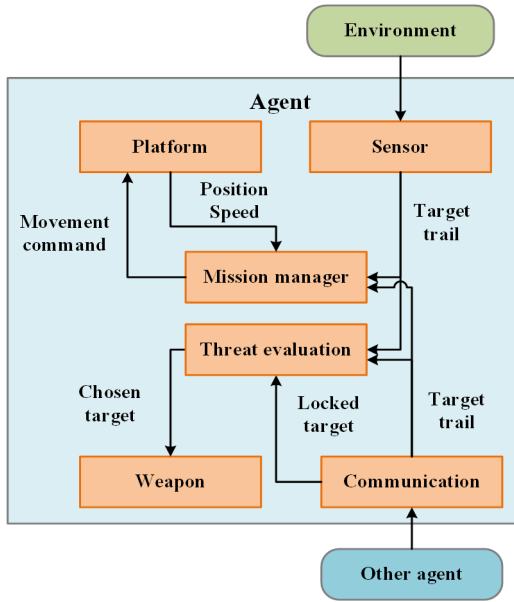In order to find out the impact of HELW to UCAV, agent-based modeling and simulation (ABMS) provides a suitable

FIGURE 4. The agent architecture.

V. SUBSYSTEM LEVEL MODEL

The impact of HELW to UCAV is divided into four parts, as shown in Fig. 5. The strike capability, stealth performance, and vulnerability impact are caused by the limited UCAV payload capability. And the power supply impact is caused by the limited UCAV power supply capability.
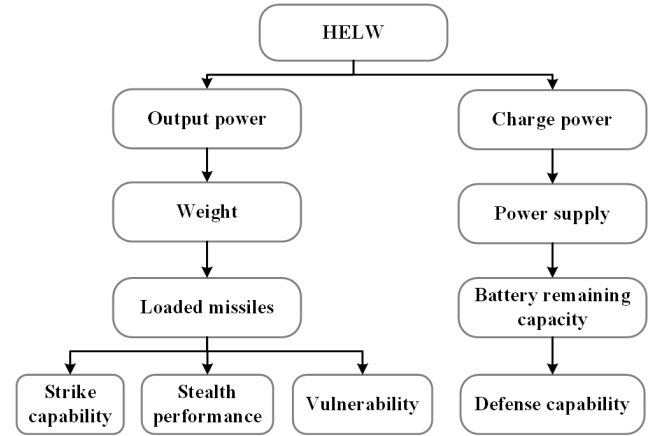

FIGURE 5. Impact of HELW on UCAV performance.

method. Agents are self-governed software models that can interact with each other autonomously. Through defining each agent behavior and their operation environment, ABMS is capable of building a complex model from the bottom up. This makes it ideal to deal with problems involving dynamic subsystem interactions, such as the penetration mission studied in this paper.

In the penetration scenario, there are three major entities, the UCAV, the missile and the air defense base, each is treated as an agent. Where the UCAV and missile agents are moveable and the air defense base agent is fixed. The UCAV agent includes all six modules, as shown in Fig. 4. While the missile agent only has platform, sensor and communication module, and the air defense base agent only have sensor and communication module. Platform module can calculate the current position and velocity of the agent with three degree-of-freedom kinetic equations. Thus, the range and angle of the target can be obtained, which is very important when calculating the dynamic laser spot power density on the target. Sensor module can calculate the target detection probability and record detected target trail. Communication module can share the detected target trails with other agents. To UCAV agent, mission manager module controls the agent to fly to the protected asset position. To missile agent, mission manager module calculates the guidance command with proportional navigation method. Threat evaluation module can calculate the threat ranking list according to the relative range of the targets and choose the highest threat that has not been locked by other agents. Weapon module can shoot the target chosen by mission manager and calculate the laser spot energy density and the laser dwell time till target destruction for the HELW. For the missile, weapon module calculates the explode timing and fragment kill probability according to the relative range when exploding.

A. STRIKE CAPABILITY IMPACT

The total take-off weight of the original UCAV W_{TO} is composed of three parts: the empty weight W_E, the fuel weight W_F, and the payload weight W_P.

$$W_{TO} = W_E + W_F + W_P \qquad (20)$$

Assume the payload W_P includes only missiles here, and the weight of each missile is W_M.

In order to achieve better survivability in hostile scenario, a HELW is equipped to defend against surface-to-air missiles. The weight of the HELW W_L depends on its output power P_0

$$W_L = P_0 \sigma_{laser} \qquad (21)$$

where σ_{laser} is the weight to power ratio of the HELW. To a given UCAV, the UCAV has to take fewer missiles to make room for the HELW. Assume the HELW is made up of n laser modules where each has an output power of P_{lm}. The integration of each module means the removal of several missiles. The missile number left n_M is

$$n_M = \frac{W_P - n P_{lm} \sigma_{laser}}{W_M} \qquad (22)$$

B. STEALTH PERFORMANCE IMPACT

Without pilots, most of the UCAVs are smaller than manned aircrafts. Limited by the inner space, the missiles have to be mounted outside the aircraft in most cases, which lead to a tremendous increase of the UCAV RCS. While the HELW is embedded inside the fuselage and causes little influence to RCS. To execute surveillance, reconnaissance, and strike operations, most UCAVs are equipped with an electro-optical pod under the fuselage, which is about the same size of the

laser turret. So, the influence of laser turret to UCAV RCS is not considered here.

In conceptual design, we can assume the increased RCS of UCAV caused by each missile is σ_M, so the total RCS of the UCAV will be

$$\sigma_{UCAV} = \sigma_0 + n_M \sigma_M \qquad (23)$$

where σ_0 is the original RCS of the UCAV without mounted missiles. The RCS of the UCAV decrease with the number of the mounted missiles as the output power of HELW increases.

C. VULNERABILITY IMPACT

The damage mechanism of anti-air missile is not only hit the aircraft directly. At most of the time, they explode near the aircraft to damage the aircraft with fragments. The kill probability of the UCAV depends on the number of fragments that hit the critical components of the UCAV. The critical area A_f of the UCAV varies with the missile number outside the aircraft

$$A_f = A_0 + n_M A_M \qquad (24)$$

where A_0 is the original critical area of the UCAV without mounted missiles, A_M is the critical area of each missile.

Assume all the fragments hit the UCAV are at the same size and speed, the directions are vertical to the critical component surface. Thus, the kill probability of the UCAV can be obtained by

$$n_f = \frac{A_f}{4\pi \sigma_R^2} N_f \qquad (25)$$

where N_f is the total fragment number of the anti-air missile, σ_R is the miss distance of the anti-air missile. The kill probability of each fragment P_{ki} can be according to by Reference [30]. Thus, the kill probability of the UCAV can be obtained by Markov chain method [31].

D. POWER SUPPLY SYSTEM CONSTRAIN

The maximum power supply capability is constant to a given UCAV, which means the charge power of the HELW battery cannot be higher than the generator's maximum output power P_T. The higher output power of the HELW is, the longer charge time it will need for each shot. But in the meantime, high output power also means shorter engage time to destroy each target. If the HELW output power is too low, the engage time for each missile will be too long, if the HELW output power is too high, the charge time will be too long, both lead to insufficient defend capability. So, a simplified power system model is built to analyze how the HELW battery capacity influences the penetration mission performance. The power system model is shown in Fig. 6. The battery discharge power is P_0/η_L, P_0 is the laser weapon output power and η_L is the electro-optical conversion efficiency of the laser device. The heat sink is assumed to be the fuel tank of the aircraft which is enough to store the HELW waste heat, so the waste heat is not considered as a constrain here. The full battery capacity is Q_0, so that the battery capacity Q_b at any time can
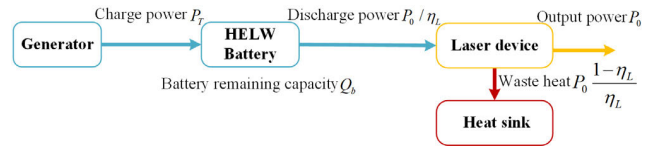

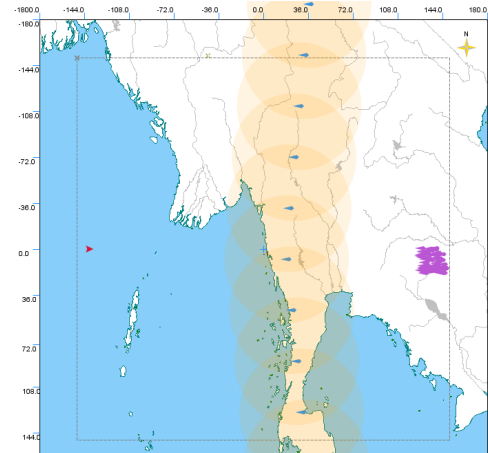**FIGURE 6.** The HELW power system model.

FIGURE 7. Demonstration of simulation scenario.

be obtained. If battery capacity decreases to zero, the HELW has to cease fire and wait for recharge.

VI. SIMULATION EXPERIMENTS

A. SIMULATION SETTINGS

The mission scenario described in section 2.1 is simplified to the simulation case shown in Fig. 7. The UCAVs are the red agents shown on the left side of the map. The air defense bases are the blue agents in the middle of the map. The radar detection area is the yellow circles around the air defense base. The protected assets are the purple agents on the right of the map. The UCAVs fly straight across the air-defense area to the protected assets and destroy them with mounted missiles. During the penetration, the UCAVs can intercept the anti-air missiles with HELW. The range between air defense bases is 30km and the protected assets are randomly deployed in an area with 20km side length.

The HELW parameters are shown in Table 1. The UCAV and the mounted missile performances are shown in Table 2. The high, medium, low level of Mach number and origin RCS of the UCAV are chosen to represent the influence of UCAV performance. The enemy radar, anti-air missile, and environment parameters are shown in Table 3.

B. SUBSYSTEM INTERACTION ANALYSIS

1) STRIKE CAPABILITY ANALYSIS

The strike capability of UCAV is mainly influenced by the number of missiles it can carry. The relationship of carried missile number of the UCAV and HELW output power is shown in Fig. 8. As we can see, the missile number decreases

TABLE 1. HELW parameters.

Parameters	Values
Weight to power ratio	5 kg/kW
HELW module power	40kW
Electro-optical efficiency	33%
Battery sustainability	10s
Sensor resolution	1296×736
FPA size	$4.8mm \times 3.6mm$
Range of focal length	[5, 50]mm
Track precision	$1\,\mu rad$
Rotate angular velocity	1 rad/s
Output mirror diameter	0.5m
Beam quality	1.5

TABLE 2. UCAV and mounted missile performance.

	Parameters	Values
	Mach number	(0.4, 1.2, 2.0)
	RCS	$(0.1, 1, 10)\,m^2$
	Payload	1200 kg
	number	10
UCAV	Max power supply	40 kW
	Critical area	$10\,m^2$
	Altitude	7 km
	Weight	100 kg
missile	RCS	$0.5\,m^2$
	Critical area	$1\,m^2$

TABLE 3. Enemy and environment parameters.

	Parameters	Values
	Reference RCS	$5\,m^2$
	Reference range	100 km
Radar	Reference detection probability	0.9
	Desired false alarm rate	10^{-6}
	Neighboring cells number	14
	Atmospheric visibility	20km
	Atmospheric density	$1.29kg/m^3$
Atmosphere	Atmospheric heat capacity	1005 J/(kg·K)
	Atmospheric reflectivity change rate	10^{-6}
	Aerosol type parameter	4.543
	Mach number	3
	Seeker reference range	20 km
	Fragment number	2000
	Shell thickness	0.01 m
Anti-air missile	Shell density	$2.7\,g/cm^3$
	Shell heat capacity	900 J/(kg·K)
	Shell surface reflectivity	0.3
	Shell damage temperature	700 K
	navigation coefficient	4

with the increase of HELW output power. As each HELW module is 40 kW and the weight to power ratio is 5 kg/kW, so that each module weights 200kg. Each integration of the HELW module leads to a removal of two mounted missiles. Thus, with the output power of the HELW between 0 kW and 200 kW, the mounted missile number ranges from 12 to 2, respectively.

2) STEALTH PERFORMANCE ANALYSIS
The stealth performance is mainly influenced by the RCS of the UCAV. Low RCS represents high stealth performance.
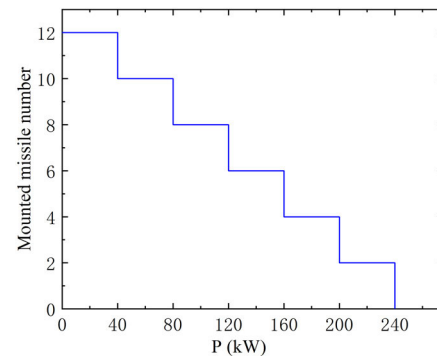

FIGURE 8. The relationship of UCAV missile number and HELW output power.
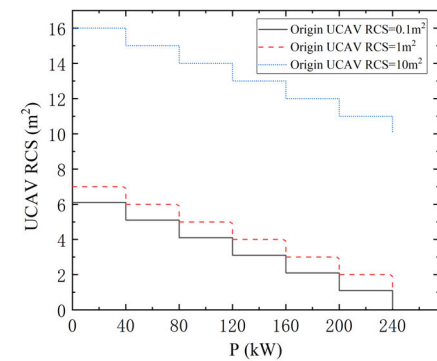

FIGURE 9. The relationship of UCAV RCS and HELW output power.

The RCS of the UCAV is composed of the original RCS of the UCAV and the increased RCS caused by the mounted missiles. Therefore, the RCS of the UCAV decreases as the mounted missile number decreases. The relationship of the UCAV RCS and HELW output power is shown in Fig. 9. The increased RCS caused by each missile is $0.5\,m^2$ to all UCAVs. Thus, to UCAV with an original RCS of $0.1\,m^2$, $1\,m^2$, and $10\,m^2$, with the HELW output power increases from 0 kW to 240 kW, the overall UCAV RCS ranges are $6.1\,m^2$-$0.1\,m^2$, $7\,m^2$-$1\,m^2$, $16\,m^2$-$10\,m^2$ respectively.

3) VULNERABILITY ANALYSIS
The vulnerability of the UCAV is influenced by the critical area of the UCAV. The missiles distributed under the wing could increase the UCAV critical area. To analyze the influence of HELW to vulnerability of the UCAV, assume the missile is exploded at a distance of 10 m, 20 m, 30 m from the UCAV, and the kill probability of each fragment is 0.05, 0.04, and 0.03, respectively. The kill probability of UCAV hit by one anti-air missile can be calculated according to the Markov chain method in reference [31]. The relationship of HELW output power and UCAV kill probability is shown in Fig. 10. As we can see, the kill probability of UCAV is highly influenced by explode distance of the missile. To 10 m explode distance, the kill probability of UCAV decreases from 0.83 to 0.56 as the HELW output power increases from
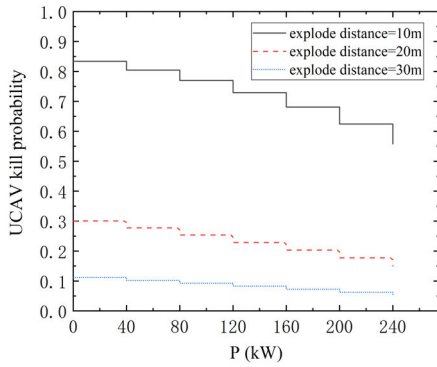
FIGURE 10. The relationship of the probability of UCAV get killed by one anti-air missile and HELW output power.

(a) 40kW HELW output power

(b) 120kW HELW output power
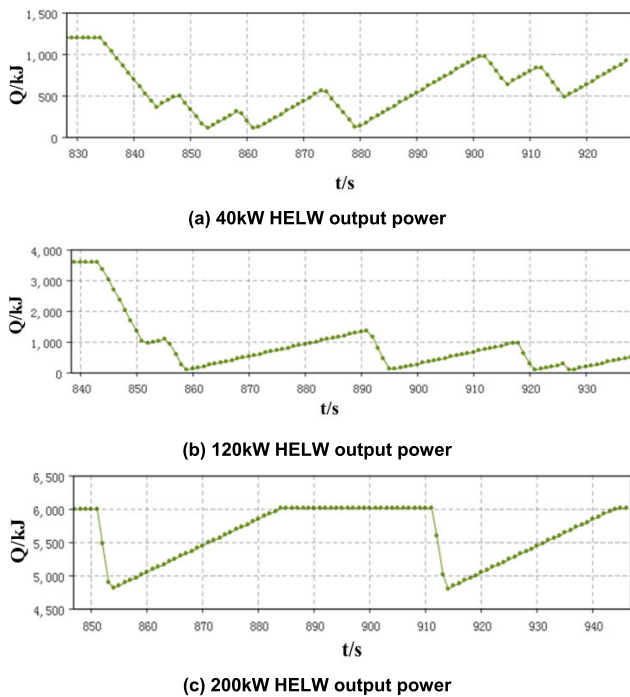

(c) 200kW HELW output power

FIGURE 11. The variation of HELW battery remaining capacity during engagement.

0 kW to 240 kW. When the explode distance is further, the kill probability of UCAV decreases dramatically, ranges between 0.3-0.15 to 20 m explode distance and 0.11-0.05 to 30 m explode distance, respectively.

4) POWER SUPPLY SYSTEM ANALYSIS

The limited power supply capacity might lead to insufficient battery capacity, and the shut-down of HELW system in the middle of engagement. For analyzing the influence of subsystem parameters to the UCAV combat performance, the cases of 40kW, 120kW and 200kW HELW output power are taken as examples. The Mach number and the origin RCS of the UCAV are 0.4 and 0.1m^2. The battery remaining capacity during engagement is shown in Fig. 11.

In the 40 kW HELW output power case, as we can see from Fig. 11(a), the UCAV encounters the first missile at 835s and intercepted 6 targets in the subsequent 100 s period, which is the earliest case and encounters the most missiles. This is because the UCAV is carrying 10 missiles outside the fuselage leading to an RCS of 5.1 m^2. It costs about 4-5 s of dwell time to destroy a missile, which is the longest. But the limited power supply capability is not a serious problem in this case because the discharge rate is relatively low.

In the 120 kW HELW output power case, as shown in Fig. 11(b), the UCAV encounters the first missile at 843 s and intercepted 5 targets in the subsequent 100 s period. The dwell time needed to destroy a target is about 3-4 s. Limited by the low charging rate, the battery capacity decreases very fast and gets empty many times. This decreases the defense capability of the HELW.

In the 200 kW HELW output power case, as shown in Fig. 11(c), the UCAV encounters the first missile at 852 s and intercepts only 2 targets in the subsequent 100 s period. This is because the RCS of UCAV is only 1.1 m^2, so that the UCAV is detected by only one air defense base during the penetration. Although the discharge rate is high, the dwell time for each target is only 2 s, and the interval between two launches is enough for recharging the battery. Therefore, the low power supply does not affect the defense capability of the HELW.

C. SOS MISSION EFFECTIVENESS ANALYSIS

Because the behavior of each agent is independent, the simulation results are randomly distributed. Multiple simulations are required to estimate the SoS mission effectiveness.

To the penetration mission studied, the mean survived UCAV number and destroyed target number are used as main factors to measure the SoS mission effectiveness. The simulation replication times is determined by the absolute error rule [29], in which the simulation keeps repeating until the half-length confidence interval of the results $l_{hCI}(n_s)$ is less than the expected absolute error β

$$l_{hCI}(n_s) = t_{n-1,1-\alpha/2}\sqrt{\frac{s(n_s)^2}{n_s}} \leq \beta \qquad (26)$$

where $t_{n-1,1-\alpha/2}$ is the t distribution's upper $1-\alpha/2$ critical point with $n-1$ degrees of freedom, n_s is the simulation times, $s(n_s)^2$ is the sample variance. The required precision here is set as 0.1. The minimum simulation times is set as 100.

The survivability of 0 kW HELW output power is 0 in all cases for the lack of defense capability, and the strike capability of 240 kW HELW output power is 0 because there is no room for missiles. Therefore, the range of HELW output power discussed here is 40 kW-200 kW.
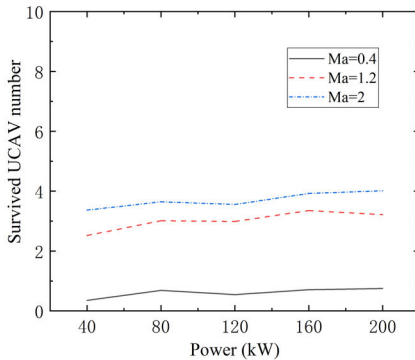
1) SURVIVABILITY ANALYSIS

The survived UCAV number is shown in Fig. 12. The UCAV survivability is strongly influenced by the UCAV performance. The survivability of the UCAV is extremely low no
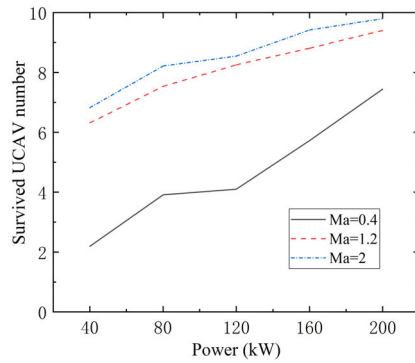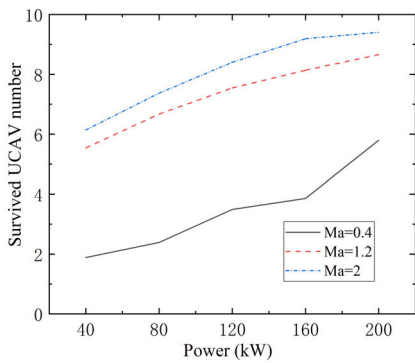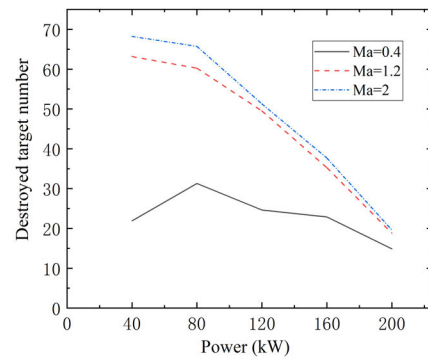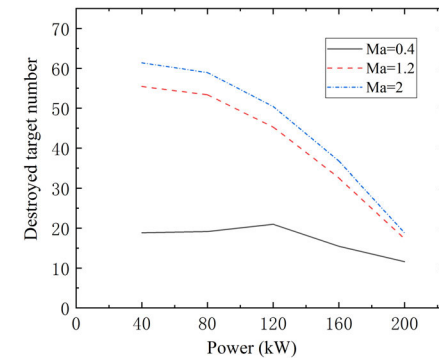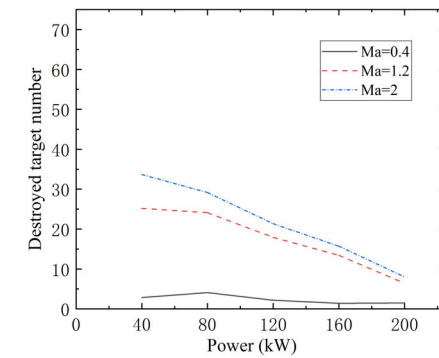
FIGURE 12. The survived UCAV number.

FIGURE 13. The destroyed targets number.

matter how much the HELW output power is when both the speed and stealth performance of the UCAV are at the lowest level. Meanwhile, more than half of the UCAVs can survive when the speed and stealth performance of the UCAV are above medium level. The growth of the UCAV survivability slows down as the speed and stealth performance increases. Anyway, the integration of HELW could decrease the design requirements for speed and stealth performance of the UCAV. And the increasement of HELW output power could lead to an increase in the UCAV survivability.

2) DESTROYED TARGET NUMBER ANALYSIS

The destroyed target number is shown in Fig. 13. As we can see, the destroyed target number peaks at 40 kW HELW output power in most cases. This is because the UCAV can carry more missiles with lower HELW output power. But in the case of 0.4 Mach number, most targets are destroyed around 80 kW-120 kW. This is because the survivability of the UCAV is too low and needs higher HELW output power to enhance its defense capability. The growth of the destroyed target number slows down as the speed and stealth performance increases. The above analysis demonstrates that the combination of a relatively high UCAV performance and a low HELW output power might be a suitable choice.

3) SOS MISSION EFFECTIVENESS ANALYSIS

The cost coefficients α_1, α_2, β_1, β_2, and γ in (2) are 0.5, 1, 5, -1, and 0.0125, respectively. The mission effectiveness
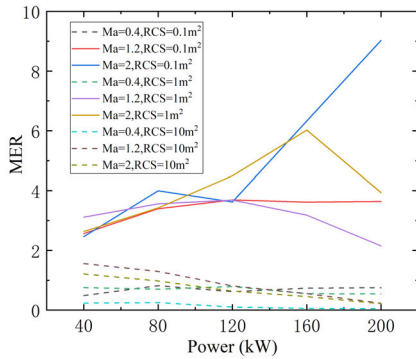
FIGURE 14. The mission effectiveness rate.

rate MER is shown in Fig. 14. As we can see, the MER is strongly influenced by the UCAV performance. The MER is very small as long as one of the UCAV design parameters is at low level, as the dotted lines at the bottom of the diagram. To UCAV with both design parameters above medium level, as the solid line in the middle of the diagram, the MER is much better. This illustrates that the UCAV performance is still very important even equipped with HELW.

The variation of HELW output power has no obvious influence to MER at most of the cases. sometimes, the MER even decreases with the increasement of HELW output power. Only in two cases, the HELW output power has obvious influence to MER, as the blue and yellow solid line in Fig. 14. Both cases have high UCAV performance, but their MERs are not monotonically increasing with the increasement of the HELW output power. This illustrates the importance of balancing the UCAV and HELW performances.

VII. CONCLUSION

This paper proposes an improved 4-level SoS oriented design method for evaluating the impact of the HELW design parameters to the UCAV mission effectiveness. The correlated subsystem constraints are considered at the bottom level so as to enable further design optimization. Simulation experiments show that HELW can increase the survivability and mission effectiveness rate of UCAV significantly. Nevertheless, high speed and stealth performance is still very important in future UCAV design. The increase of HELW output power dose not lead to an increase of MER in most of the cases. To obtain a high MER, the balancing of UCAV and HELW design parameters is very important. Possible future work can be carried out to refine the subsystem models and improve the fidelity of simulation results by modify the models used with more details.

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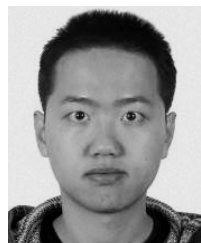
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