



Review

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Current status and prospects of terminal guidance laws for intercepting hypersonic vehicles in near space: a review

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Abstract: The unique performance advantages of hypersonic vehicles represent a critical challenge for existing defense systems. To facilitate defensive operations against hypersonic vehicles in near space, this paper systematically discusses both the advantages of these vehicles and the difficulties in intercepting them. Focusing on the state-of-the-art terminal guidance laws for intercepting hypersonic vehicles in near space, we examine research progress in the area of single- and multi-interceptor cooperative guidance laws and summarize their advantages and disadvantages. We also highlight future research directions for developing an effective terminal guidance law for multi-interceptor cooperative interception of hypersonic vehicles, based on four aspects: the information domain, space domain, physical domain, and effect-cost ratio. The findings provide a reference for further research into near-space interceptor terminal guidance technologies.

Key words: Hypersonic vehicles; Guidance law; Cooperative guidance; Near space

1 Introduction

Advancements in ramjet engine and flight control technologies have led to the rapid development of hypersonic vehicles, which are defined as vehicles capable of sustained flight at hypersonic speeds (excess of Mach 5) in near space (Acton, 2015; Chen et al., 2021; 2022; Zhang X et al., 2022). As shown in Fig. 1, hypersonic vehicles combine several performance advantages over conventional flight vehicles. Compared to aircraft, hypersonic vehicles are subject to less drag and therefore fly faster, allowing them to attack targets thousands of kilometers away more quickly. Compared to ballistic missiles, hypersonic vehicles exhibit a considerably higher dynamic pressure at high speeds and can implement a wide range of maneuvers (Wilkening,

2019). Overall, hypersonic vehicles exhibit the five advantages described below.

1.1 Speed advantage

Hypersonic vehicles have a notable speed advantage over their various opponents. This allows for changes in the time-space relationship and has introduced the age of the “second kill” in warfare. The Russian air-launched hypersonic vehicle “Dagger” has a maximum flight speed of approximately Mach 10 and a range of 2000 km. Its speed makes it difficult for an opponent’s ground-based and airborne sensors to detect and track it, reducing their response time capabilities (Williamson and Wirtz, 2021). Specifically, the interceptor’s speed makes conventional wireless communications more challenging during scenarios involving hypersonic vehicle communication (Shi et al., 2020). There are two reasons for this. First, the deep attenuation encountered by the interceptor’s surrounding plasma sheath tends to result in a very low received signal-to-noise ratio (SNR). Second, the relatively high-speed movement between the detector and hypersonic vehicle results in a large Doppler shift, with a magnitude of up to 1.5 MHz in the Ka band at Mach 20

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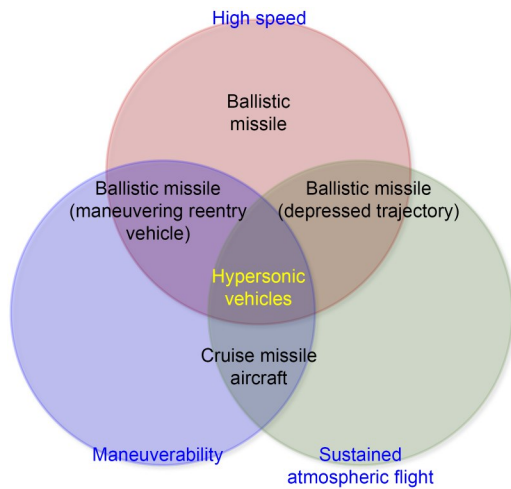


Fig. 1 Characteristics of hypersonic vehicles

(Drakes et al., 1992; Zhu et al., 2018). This seriously degrades carrier synchronization for signal recovery at the receiver end. Hypersonic vehicles can strike globally important military targets anywhere across the globe within one hour (Ekmektsioglou, 2015). Moreover, such vehicles can effectively perform military missions (such as intelligence gathering and strikes) and civilian missions (such as rapid transport) which are typically difficult to accomplish with ordinary aircraft. Because of the speed advantage, the maneuvering capabilities of hypersonic vehicles are more strongly coupled with the information and decision elements, which can accelerate the observe-orient-decide-act (OODA) kill chain, lead to information and decision superiority, and induce the dimensionality-reduction strike effect. Regarding the latter, being in the same dimension as the opponent requires both parties to follow the same rules of war, and in such cases, the speed advantage of hypersonic vehicles can disrupt the opponent's conventional defense system.

1.2 Mechanism advantage

The mechanism advantage can lead to realization of “exponential kill.” Kills by traditional munitions are typically based on chemical-energy conversion and release. Consequently, the kill ability of such munitions in combat is constrained by several factors, such as the munitions carrier; it may be challenging to strike solid or underground targets. According to the kinetic energy theorem, the kinetic energy of an object is proportional to its mass and the square of its speed (Lawson and McDermott, 1987). When a flight vehicle reaches

hypersonic speeds, its kinetic energy is exponentially multiplied; this enhances the destructive effectiveness of the warhead. The kinetic energy associated with the impact of a 1.5-kg hypersonic missile warhead is sufficient to collapse a bridge (Li and Meng, 2020). A hypersonic vehicle that carries a penetrating warhead can reach depths of more than 10 m in reinforced concrete. This allows it to strike solid targets such as command centers that are buried deep underground. Thus, realization of hypervelocity kinetic kills can induce the “exponential kill” effect in warfare.

1.3 Agility advantage

The agility advantage refers to the generation of responses to the opponent's actions. Hypersonic vehicles have multiple payloads and can undertake multiple missions, such as long-range rapid and precise strikes, strategic and tactical reconnaissance, and delivery on a global scale. Moreover, their excellent speed and combat capability allows them to change their maneuvering trajectories and gives them notable operational agility. This ability can create uncertainty in targets, leaving them with diminished defense capabilities and making it easy to penetrate their defenses. Additionally, hypersonic vehicles can hit a wide range of fixed and time-sensitive targets. By integrating the speed advantage of ballistic missiles and the variability of cruise missiles, hypersonic vehicles have become the most powerful type of weapon after nuclear weapons.

1.4 Application advantage

The application advantage is evident with regard to both deterrence and hit capabilities. Air and space assault vehicles that involve hypersonic vehicles have the strategic advantage of first strike and deterrence. At the macro level, the emergence of such vehicles influences strategic power balances, which affects strategic intent and determination. At the micro level, the power layout of the combat opponent is affected, leading to forced adjustment in the deployment of combat forces. Moreover, when used as a conventional rapid strike system, hypersonic vehicles exhibit superior operational effectiveness and kill power. Because the collateral lethality is lower than that of nuclear weapons, negative public opinions and moral pressure are minimized, avoiding the political risks and high thresholds associated with nuclear use can be avoided. This allows hypersonic vehicles, which are already highly deterrent

and extremely effective attack vehicles, to have several strategic applications.

1.5 Cost advantage

The cost advantage pertains to an asymmetric counterweight effect, and is a reflection of the high-cost performance and asymmetric offset against operational opponents. Although the development of hypersonic vehicles, from pre-research to system construction, is expensive, the cost is reasonable compared to the development and construction of complex defense systems. The disruptive operational capabilities of hypersonic vehicles can render existing defense systems useless, meaning that money invested in the development of air-defense and anti-missile systems can be considered wasted. This asymmetric offset endows hypersonic vehicles with a significant cost advantage. For this reason, Russia uses hypersonic vehicles as an asymmetric counterweight to the USA, accelerating their deployment to create an asymmetric offset to multiple US interceptor defense systems.

Given the remarkable potential of hypersonic vehicles in military applications, many military powers have performed extensive research on them as part of long-term investments in research and development (Bolender and Doman, 2007; Xu and Shi, 2015; Zhang et al., 2021a, 2021b; Ding et al., 2022). Table 1 shows how the USA has highlighted hypersonic vehicles as a key priority for the Department of Defense, and hypersonic missile development programs have been undertaken by the army, navy, and air force. The Defense Advanced Research Projects Agency is also accelerating engineering and practical development in this area (Sayler, 2019; Work and Grant, 2019; Davis, 2020). Since 2017, Russia has taken the lead in commissioning three types of hypersonic vehicles: the Dagger, Vanguard, and Zircon (Banasik, 2021); these represent strike systems for use over sea, land, and air, further advancing the competition for hypersonic vehicles. At

present, development of hypersonic vehicles has progressed towards the weaponization stage, and nuclear weaponization may also be underway (Gubrud, 2015; Nagappa, 2015; Zhao, 2015).

In February 2019, the United Nations Office for Disarmament Affairs (UNODA) released “Hypersonic Weapons—A Challenge and Opportunity for Strategic Arms Control” (Borrie et al., 2019). This report notes that hypersonic weapons have not yet been included in the UN arms-control regime, and that their rapid development poses a major challenge to the stability of the arms-control mechanisms that have been honed over half a century, for two reasons. First, the emergence of such vehicles is expected to drive a new arms race. The UNODA has always believed that there will always be one side seeking absolute superiority of hypersonic vehicles at the international level, and that the resulting imbalance in offensive and defensive postures would further promote the willingness of different countries to engage in an arms race. In this context, development of hypersonic vehicles can help countries satisfy many of the conditions necessary for absolute superiority at the current level of technology.

Second, strategic miscalculations could lead to escalations in adverse situations. Hypersonic vehicles can perform rapid nuclear and conventional strikes from offensive positions. In defensive situations, the time available to make decisions significantly decreases, while the complexity of decisions significantly increases. This raises the likelihood of strategic miscalculation and subsequent escalation (Zhang, 2019).

Without the ability to intercept these vehicles, a lack of security exists. At the country level, the acceleration of research on interception technology for hypersonic vehicles should help fill the gap in near-space defense capabilities and close defense loopholes. By improving the ability both to deter combat and to fight, and taking into consideration the existing international landscape of weapons and equipment, countries can enhance their overall security level. At the international

Table 1 Budget of USA offensive hypersonic missile programs

Program	FY2020 (×10 ⁶ USD)	FY2021 (×10 ⁶ USD)	Design schedule
Conventional quick strike	512	1008	Initial operational capability by 2028
Long-range hypersonic weapons	404	801	Completion of flight test before 2023
Air-launched rapid-response weapons	286	382	Completion of flight test before 2022
High-speed conventional striking weapons	290	0	Cancelled development plan in 2021
Tactical boost glide weapons	152	117	Completion of flight test before 2021
Combat firepower weapons	50	40	Completion of flight test before 2021

level, developing interception technologies for hypersonic vehicles could have several significant outcomes. First, it could limit the willingness of opposing countries to use weapons in near space, as well as the conditions in which they would be used. This would also increase the effectiveness of hypersonic vehicles as a deterrent, reducing their use to something more like that of ballistic missiles or long-range bombers. This paradigm would ensure a balance of offensive and defensive systems and increase the stability of the world military landscape. Developing the technologies for intercepting hypersonic vehicles is therefore not only an academic task, but a highly relevant one, both now and in the future.

This review aims to systematically analyze the difficulties in intercepting hypersonic vehicles during the terminal guidance phase. It summarizes the existing terminal guidance laws for intercepting hypersonic vehicles and provides an outlook for the design of future terminal guidance laws based on the context of near-space defense operations.

2 Difficulties in intercepting hypersonic vehicles

Hypersonic vehicles, with their unique advantages, are expected to have a profound impact on the battlefield environment. Defensive operations in near space encounter four specific difficulties: discovery, detection, tracking, and interception.

2.1 Discovery

Hypersonic vehicles have long flight ranges; the distance between their launch sites and destinations may be thousands or even tens of thousands of kilometers. Consequently, their detection necessitates the use of space-based detection platforms or long-range early warning radars. Notably, the existing long-range warning systems exhibit three limitations in addressing the threat of hypersonic vehicles: space-based early warning system capabilities, ground-based early warning capability, and target identification capability. First, space-based early warning systems can only detect vehicles within a limited airspace (Fu et al., 2017). For ground-based early warning systems, the small radar cross-section of hypersonic vehicles, along with plasma sheathing, lead to high false-alarm rates and weak search

capabilities (Bian et al., 2021). Third, it is difficult to effectively identify targets as there is no database of hypersonic vehicle characteristics (Bian et al., 2020).

2.2 Detection

Fig. 2 shows that hypersonic gliding vehicles (HGVs) spend most of their flight time in the lowest 100 km of the atmosphere. Such vehicles rely on lift force for long flight times in the thin atmosphere of near space; they also perform lateral maneuvers to create a large strike area (Xie et al., 2011). As shown in Fig. 3, because of physical constraints such as the curvature of the Earth, the closer an HGV travels to the ground, the more difficult it is to detect and intercept for most of its flight time. Ground-based radars may not detect the target until late in its flight. Such hysteretic detection shortens the time available for decision-makers on the defensive side to assess their response options and for defense systems to intercept the vehicles. In most cases, only one interception attempt is possible, and a failed interception would be fatal to the defensive side.

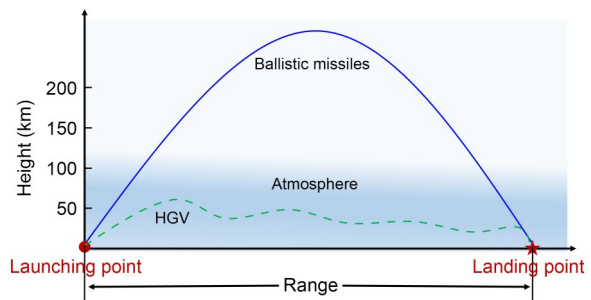


Fig. 2 Flight profiles of hypersonic gliding vehicles (HGVs) and ballistic missiles

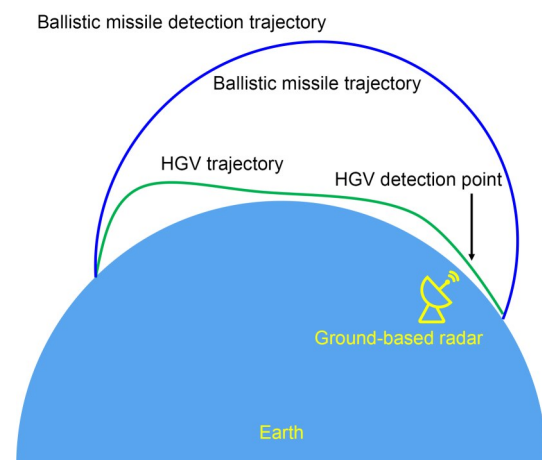


Fig. 3 Ground-based radar's detecting difference between HGVs and ballistic missiles

2.3 Tracking

Hypersonic vehicles travel faster than most radar data processing wavelength gates, meaning that the target is difficult to track, assuming it can be detected. In addition, the defensive side cannot predict the instant, amplitude, or frequency of future target maneuvers (Guo et al., 2013; Hu et al., 2021; Zhang JB et al., 2022). Although researchers have achieved several promising results in their attempts to track maneuvering targets, tracking targets that are maneuvering frequently remains a challenging problem with high technical requirements, both in theory and in engineering practice.

2.4 Interception

Air-breathing hypersonic vehicles generally fly at Mach 5–6 for long periods, and HGVs can reach speeds of Mach 15–20 (Zhao et al., 2014; Sziroczak and Smith, 2016; Sayler, 2019). However, existing interceptors typically fly at speeds lower than Mach 4 (Liu et al., 2022b). The speed advantage of hypersonic vehicles decreases the area in which they can be intercepted and accelerates their line-of-sight divergence during encounters. This widens the potential distance that an interceptor can be off-target and also decreases the interception success rate. In addition, hypersonic vehicles do not have a fixed trajectory during flight, and the air density in the primary flight space is extremely low. Consequently, the rudder efficiency is low, and the interceptor must be controlled using an attitude-control and orbit-control power system. All of these factors make continuous, rapid, and accurate control of the attitude-control and orbit-control engines challenging.

3 Terminal guidance laws for intercepting hypersonic vehicles

Guidance laws form the core of interceptor guidance systems. Based on information obtained in real time, these systems generate guidance commands subject to specific constraints, and guides the interceptors to the target in an appropriate manner (Hu et al., 2018; Han et al., 2022a, 2022b). Consequently, the performance of a guidance law determines, to a certain extent, the effectiveness of the interceptor. In near-space defense operations, the advantages of hypersonic vehicles and the challenges in intercepting them mean that the terminal guidance distance of the interceptor is

small and only a limited terminal guidance time is possible (approximately 10 s). Consequently, guidance laws must be effective in achieving a hit-to-kill effect in a short period. In general, based on the number of interceptors, guidance laws can be classified into single-interceptor and multi-interceptor guidance modes.

3.1 Single-interceptor guidance laws

3.1.1 Classical guidance laws

Classical guidance laws include the tracking method, the parallel approach method, the three-point method, the pre-measurement method, and the proportional navigation guidance (PNG) (Pastrick et al., 1981; Nielsen, 1988; Dimirovski et al., 2004). PNG is widely used in engineering practice because of its simple form and ease of implementation (Yang and Yang, 1996a, 1996b). Based on differential geometry theory and PNG, a composite guidance law has been established (Zhao et al., 2020), which can accelerate the convergence of the line-of-sight angular rate, ensure that the interceptor can successfully intercept hypersonic targets in a short time, and decrease the possibility of target escape. Another guidance law based on PNG has been proposed for intercepting high-speed maneuvering targets (Kumar et al., 2017). This guidance law predicts the target's trajectory by employing a linear extrapolation method and rotation-correction strategy. This allows the interceptor to predict the future position of the target and move toward it in real time without estimating its acceleration. In this manner, it is possible to prevent degradation of interceptor guidance performance due to inaccurate acceleration information. It is noteworthy that guidance laws based on PNG or its variants exhibit higher guidance accuracy when intercepting targets that are stationary or moving at a constant speed, rather than targets that are maneuvering. When targeting hypersonic vehicles, PNG is prone to overload saturation, meaning that effective guidance commands cannot be provided. This leads to an increase in or even divergence of the angular rate of the line-of-sight at the end of the interception and failure of the interception mission (Ye et al., 2017; Li et al., 2018; Liu et al., 2022e).

3.1.2 Modern guidance laws

With advancements in modern control theory and computer technology, many modern control techniques have been applied to the design of terminal guidance

laws for interceptors in order to satisfy the intensifying guidance performance requirements. Examples include sliding mode control, differential countermeasure, optimal control, fuzzy logic, and neural-network control methods.

(1) Guidance laws based on sliding mode control

Sliding mode control (SMC) is robust to bounded model uncertainties and external disturbances that satisfy the matching conditions and is characterized by a simple structure, easy implementation, and fast response (Chalanga et al., 2016; Yan et al., 2019; Han et al., 2021; An et al., 2022b). Consequently, it has been widely applied in the design of interceptor guidance laws. For example, a sliding mode guidance law with field-of-view constraints was designed for naval targets while considering the practical working capability of the guidance head (Liu et al., 2021). To enhance the performance when tracking and intercepting low-altitude targets, a nonlinear integral sliding mode guidance law with strong fault tolerance was proposed by Chen et al. (2019) to ensure that the line-of-sight angle converges to a desired tracking angle in finite time. Moreover, a sliding mode guidance law with terminal impact angle constraints was proposed by Zhang and Yang (2018). In this framework, a fast-converging non-singular terminal sliding mode control algorithm is adopted to achieve non-singular, finite-time convergence. To address the problem of hypersonic vehicle interception, a head-pursuit finite-time sliding mode guidance law was established by designing a finite-time disturbance observer (Zhu and Guo, 2019; Zhu, 2021). The formulation was based on the dynamic characteristics of the interceptor guide head and the maneuvering characteristics of targets. Using this framework, Liu et al. (2022c) introduced fractional-order operators into the sliding mode surface, and a fractional-order sliding mode guidance law was designed for intercepting hypersonic vehicles with small interceptor-to-target speed ratios. This guidance law ensured interception accuracy and decreased the interceptor's energy consumption, unlike the integer-order sliding mode guidance law.

Notably, it is difficult to select guidance parameters for guidance laws based on sliding mode control methods, and challenging to avoid chattering of guidance commands during the guidance process. In addition, most guidance laws based on SMC require accurate maneuvering information for the targets and do

not consider optimal performance metrics. Consequently, the interceptors typically cannot perform interception missions against targets at medium to long range (Sun and Liu, 2017).

(2) Guidance laws based on optimal control

Compared to traditional guidance laws, laws based on the optimal control theory can optimize the performance indicators of the interceptor (e.g., maximizing energy saving or minimizing interception time) by ensuring guidance accuracy (Park et al., 2013; Ai et al., 2019; Sun and Liu, 2019). In general, several terminal constraints, such as impact angle and overload constraints, must be considered to satisfy the requirements of different interception scenarios. An optimal guidance law with both impact time and impact angle constraints was proposed by Chen and Wang (2019) using the small-angle assumption. The constraints were satisfied by introducing a feedback controller, and the singularity problem of the guidance laws was solved. Based on this framework, a two-stage guidance law using virtual target approach was established by Zhang ZH et al. (2022) for attacking stationary targets with both impact time and impact angle constraints. In the first stage, the guidance law was in the energy-optimal closed-loop analytical form and aimed at attacking a virtual target with zero impact angle. In the second stage, the PNG was used to enhance the robustness to potential interference and ensure the smoothness of the two-stage guidance law in the switching process.

To ensure that the target could increase its safe distance and was protected from defense and interception, a 3D nonlinear optimal defensive guidance law was proposed by Fang et al. (2019) and used to establish an algorithm for rapidly predicting the trajectory of an attacking interceptor. Considering the problem of cooperative encirclement and simultaneous attack by multiple unmanned aerial vehicles, and assuming that target acceleration could be estimated, Wei et al. (2021) used the variational method and Hamiltonian optimization to design optimal attack trajectories for multiple attackers on a single target, with fixed initial and final relative states and fixed attack duration. Furthermore, a linear quadratic optimal-control guidance law considering obstacle avoidance was designed to address the problem of intercepting maneuvering targets by introducing a bias term based on PNG (Weiss and Shima, 2019).

It is important to note that guidance laws based on optimal control typically assume that the motion of the target is known. However, a target may maneuver to protect itself from the interceptor. In addition, most of these guidance laws are based on linearized models which differ significantly from the actual guidance models, leading to inferior guidance accuracy in practical applications.

(3) Guidance laws based on differential countermeasure

The differential countermeasure theory was established to solve dynamic game problems (Mitchell et al., 2005; Hua et al., 2016). The pursuit-evasion problem is a typical dynamic game problem in which the interceptor tries to use the best strategy to attack the target, while the target tries to use the best strategy to escape. Taking the case of interceptors and targets with first-order dynamic response characteristics and ideal response characteristics, Gutman (1979) applied the differential countermeasure theory with terminal constraints to design optimal guidance laws for interceptors that take into account bounded constraints on the overload on both sides of the countermeasure. Estimation of the zero-off-target corrections was also optimized by applying target orientation information to reduce the reachable set of target acceleration, and a differential-countermeasure guidance law was established for short-range air-to-air interception in the horizontal plane (Oshman and Rad, 2006).

In other studies (Hua and Chen, 2011; Hua et al., 2011), researchers designed a differential countermeasure guidance law by linearizing the guidance model of a speed-controlled interceptor, and evaluated the performance index for differential countermeasures with impact angle constraints. To facilitate interception of hypersonic vehicles with a small interceptor-to-target speed ratio (i.e., the speed of the interceptor is lower than that of the hypersonic vehicle), the nonlinear differential countermeasure theory was used to transform the hypersonic vehicle interception problem into one that requires solving the state-dependent coefficient and algebraic Riccati equations. Furthermore, an analytical form of the differential countermeasure guidance law based on the state-dependent Riccati-equation approach was recently presented by Liu et al. (2022d). This guidance law does not require calculation of the interceptor's remaining time of flight, and the relative movement between the interceptor and target is taken into account.

Notably, in actual interception scenarios, the guidance accuracy of most differential countermeasure guidance laws depends on an estimation of the interceptor's remaining flight time. In practice, the remaining flight time is often difficult to accurately estimate. Therefore, in practical applications, the guidance accuracy afforded by guidance laws based on the differential countermeasure may be inadequate.

(4) Guidance laws based on fuzzy logic

Fuzzy control, a representative intelligent control method, uses fuzzy language and reasoning to approximate nonlinear systems for which it is challenging to establish an accurate mathematical model. Such frameworks enable accurate and robust control of nonlinear systems (Zhong et al., 2019; Dumitrescu et al., 2021; Riaz et al., 2022; Tang et al., 2022; Liu et al., 2023). The concept of fuzzy control was first introduced in the design process of guidance laws to obtain a basic fuzzy-control guidance law (Mishra et al., 1994). Later, Elhalwagy and Tarbouchi (2004) introduced a composite guidance law based on fuzzy control theory that adaptively updated the conventional sliding surface parameters. This framework adaptively compensated for the effects of the unmodelled dynamic part of the guidance system and mitigated chattering in the guidance commands.

For hypersonic vehicles, Lin and Chen (2000) proposed a guidance law based on fuzzy control theory. This guidance law provides better interception conditions before the interceptor enters the terminal guidance phase, thereby enabling a smaller zero-off-target and wider interception range than those achievable using PNG. Hassan et al. (2013) used this concept to establish a two-stage guidance law by designing fuzzy switching points. This guidance law was adequately robust to target maneuvers and could simultaneously smooth guidance command distribution and enhance guidance accuracy. Other researchers, such as Li et al. (2016) established a fuzzy sliding mode control guidance law with impact angle and guidance command constraints for attacking stationary targets; it combined sliding mode control algorithms with fuzzy-logic control schemes but omitted a lag system and first-order lag system. Subsequently, Wang et al. (2018) proposed a fuzzy sliding mode control guidance law that considered the available overload and autopilot dynamics of the interceptor with regard to maneuvering targets. In this framework, adaptive neural networks were used

to compensate for the external disturbance information associated with target maneuvering.

It is noteworthy that the existing design strategies for fuzzy control are not systematic. During the actual motion process, the interceptor's motion state may be jointly affected by the environment, climate, target, actuator, and other factors, and simple fuzzy processing may lead to low guidance accuracy and system dynamic quality. Furthermore, fuzzy control rules are typically based on expert experience and knowledge. The ability of a natural architecture to describe human behavior and decision-making influences the system's control effect.

(5) Guidance laws based on neural-network control

Neural-network control methods are aimed at modelling complex nonlinear objects that are difficult to accurately describe. Neural networks are employed to achieve nonlinear control, using neurons as the basic nodes (Cheng et al., 2021; Federici et al., 2021; Izzo and Öztürk, 2021). Based on fuzzy control and neural-network control methods, some researchers (Geng et al., 1995; Geng and McCullough, 1997) designed a closed-loop neural-network terminal guidance law. Moreover, assuming the target acceleration information to be a bounded disturbance, Li ZJ et al. (2015) explored the design of a neural network based on model predictions of the terminal guidance law. The guidance law design process was transformed into a constrained quadratic programming problem using linear variational inequalities and pairwise neural networks to obtain the analytical solution of the guidance law. To facilitate interception of targets with constant maneuverability, a neural-network control method was used to design a terminal guidance law (Cottrell et al., 1996). Simulation results showed that the proposed law could optimize the size and weight of the interceptor during operations when minimal changes occurred in the transfer incremental speed of the interceptor along the interception trajectory.

To improve the target kill effect, a guidance law with impact angle and guidance command constraints was designed for stationary targets by using a wavelet neural network (Li QC et al., 2015). This guidance law adaptively updated additional control commands to reduce the signal chattering caused by sliding mode control. A finite-time guidance law for high-speed maneuvering targets was designed by Wu and Zhang (2021), and considered the constraints of the impact

angle, guidance command, and dynamic characteristics of the autopilot. Based on the backstepping method, this guidance law had a virtual control command and nonlinear first-order filter that overcame the differential expansion problem of the traditional backstepping method. To address the external disturbances caused by target acceleration at unknown boundaries of the guidance system, an adaptive radial-basis-function (RBF) neural-network interference observer was established to estimate the interference information of the target online and ensure the accuracy of the guidance system. This guidance law was extended to 3D space by Wu et al. (2022), and a fast non-singular terminal sliding mode surface and an adaptive law were established to compensate for error in the RBF neural-network when estimating target maneuver information, thereby increasing the convergence speed of the guidance system.

Although the neural-network control method can enhance guidance performance to a certain extent, a guidance law designed for offline training method is sensitive to new target information and environmental information; this can degrade guidance performance and lead to failure of the combat mission (Gu et al., 2008). For guidance laws designed in the online real-time training mode, the neural networks are in the large-scale state space during training, which may lead to inefficient convergence of the neural network because of the high requirements for allocation of onboard computing resources.

3.2 Multi-interceptor cooperative guidance laws

Accurate interception of hypersonic vehicles by a single interceptor is typically challenging because of (1) the high flight speed, strong lateral maneuverability, and vast operational airspace of hypersonic vehicles, and (2) the limited flight speed and maneuverability of interceptors. Multi-interceptor cooperative guidance allows multiple interceptors to form a combat group with shared information, complementary functions, and tactical synergy. The advantages of the group are exploited to conduct multi-level, all-round strikes against opponent defense systems and targets, thereby enhancing defense penetration capability (Zhao and Yang, 2017; Chen et al., 2021; An et al., 2022a). Based on a second-order multi-agent consensus protocol, Zhao et al. (2016) established a heterogeneous cooperative guidance law with a leader-follower structure (the leader was equipped with a high-performance guidance head,

while the follower was not) for intercepting hypersonic vehicles. This framework reduced the need for guidance equipment for the group, enhanced the effect-cost ratio, and facilitated effective interaction in both fixed and switched topology conditions.

To promote the interception of hypersonic vehicles, guidance commands in two separate directions were designed by dividing the guidance system into two directions: along the line-of-sight directions and along the vertical line-of-sight directions (Tan et al., 2019; Liu et al., 2022a). In the first case, a multi-agent consensus protocol was used to achieve simultaneous arrival of the interceptor group in the time dimension. For the latter one, a sliding mode control method was applied to intercept hypersonic vehicles with impact angle constraints. Moreover, the concept of an interceptable zone and predictable interception zone for interceptors was proposed by Wang et al. (2022). The range of the predictable interception zone for each interceptor was predicted by designing the interceptor performance index function and enabling the concatenation of the interceptable zone for each interceptor in the group to cover the maneuvering range of hypersonic vehicles.

The existing multi-interceptor cooperative guidance laws for the interception of hypersonic vehicles can be divided into two categories. The first category is based on multi-agent consensus protocols. The interception time of each interceptor is constrained to ensure simultaneous arrival by considering variables such as the relative distance between the interceptor and target and remaining flight time of the interceptor. These guidance laws can exploit the combined interception capability of each interceptor, thereby generating a combined siege posture against hypersonic vehicles and achieving a $1+1>2$ interception effect. However, such guidance laws require the existence of global or partial communication among the interceptors to ensure that their motion state can be adjusted to achieve simultaneous arrival. If the communication network fails, the motion state of the interceptor group may not be consistent within a limited period, leading to failure of cooperative guidance. In addition, the consensus posture of the interceptors may be disrupted once the motion of hypersonic vehicles changes because of the large speed difference between the two types of vehicles. In this scenario, the interceptors may fail to arrive simultaneously.

The second category is based on predicting the flight trajectory of hypersonic vehicles. Multiple interceptors are launched within a certain time interval to form an interception posture with a hierarchical distribution in time and space. The objective is to ensure that at least one interceptor can accurately intercept the hypersonic vehicles during middle and terminal guidance handover. Such guidance laws provide updated and accurate information in real time for subsequent interceptor launches by fusing and sharing the information detected by each guidance head, thereby increasing the probability of intercepting the hypersonic vehicles and providing a reference for medium and terminal guidance handover conditions. However, when hypersonic vehicles maneuver, the information detected by individual interceptors is likely to deviate, allowing the target vehicles to evade interception by a single interceptor launched subsequently.

4 Future work outlook

Table 2 summarizes the advantages and disadvantages of the existing terminal guidance laws for intercepting hypersonic vehicles. Although promising results have been obtained in this area, the existing interceptors are inferior to hypersonic vehicles in terms of flight speed and maneuverability, and a single interceptor may not be effective in complex battlefield environments. Moreover, the existing studies on terminal guidance laws based on a single interceptor have not fundamentally overcome the challenges encountered in intercepting hypersonic vehicles. There remains considerable scope for enhancing the design of terminal guidance laws to include multi-interceptor cooperative interception of hypersonic vehicles.

In the following subsections, we highlight several technologies that will be important when developing terminal guidance laws that can facilitate multi-interceptor cooperative interception of hypersonic vehicles and allow existing defense systems to adapt to complex battlefield environments.

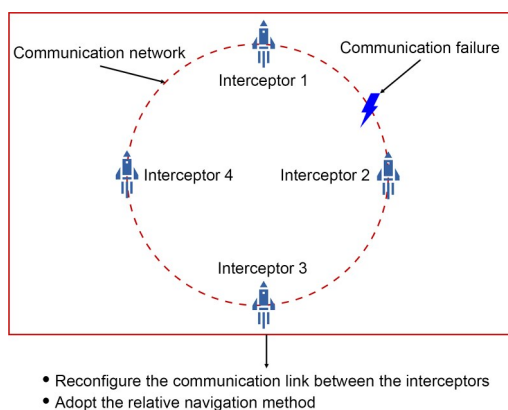
4.1 Design based on the information domain

For multi-interceptor cooperative guidance laws based on multi-agent consensus protocols, inter-interceptor communication is the key for a successful mission. Notably, communication complexity increases

Table 2 Advantages and disadvantages of the existing terminal guidance laws for intercepting hypersonic vehicles

Category	Method	Advantage	Disadvantage
Single-interceptor guidance law	PNG	Simple form, easy implementation, and high robustness	Prone to overload saturation against high-speed maneuvering targets as the line-of-sight angle rate diverges
	SMC-based	Simple form and high robustness to uncertainty and disturbances	Parameter selection is challenging and guidance command chatter is unavoidable
	Optimal control-based	Achieves the desired performance, subject to certain constraints	Nonlinear models may deteriorate guidance accuracy in practical applications
	Differential countermeasure-based	Fully considers the game relationship between interceptor and hypersonic vehicle	Nonlinear models may deteriorate guidance accuracy in practical applications
	Fuzzy logic-based	Approximate nonlinear systems with high robustness	Mainly based on the experience and knowledge of experts
	Neural-network control-based	Alleviates excessive dependence on guidance models	Limitations in the training process
Multi-interceptor guidance	Multi-agent consensus-based	Performs a saturation attack against targets	Some burdens caused by global or partial communication
	Trajectory prediction-based	Yields an interception posture with a hierarchical distribution in time and space	Ineffective when hypersonic vehicles execute maneuvers

geometrically with the number of interceptors (Liu et al., 2019). If the interceptor group cannot autonomously cope with sudden failure of inter-interceptor communication caused by inadequate performance of the data chain, actuator failure, or external electronic interference, the advantages of multiple interceptors become difficult to exploit. Moreover, the motion status of each interceptor in the group may be inconsistent, which may have catastrophic consequences. Fig. 4 shows two potential solutions for this problem.

**Fig. 4 Cooperative guidance law based on the information domain**

First, in events that involve disrupted group communication chains, the chains can be reconstructed. The objective is to select alternative communication

links that can satisfy the communication conditions for the interceptors that are affected by the malfunction. This can enhance the reliability of the group's communication network if it has limited communication resources, and optimize the cost of communication among the interceptors.

Second, in cases where the communication nodes cannot be repaired (i.e., the communication link cannot be reconstructed), the impact of communication failure on cooperative guidance can be alleviated using relative navigation techniques based on the relative motion information between the interceptors and hypersonic vehicles. When an interceptor in the group encounters a severe communication failure that results in an inability to share and interact with other interceptors, relative navigation technology can assist the interceptor in using motion information (such as the position and speed of its surrounding interceptors) to adjust its own motion state (Dong and He, 2021). This indirectly ensures the stability of the interceptor group system and prevents the failure of cooperative interception.

4.2 Design based on the space domain

Most of the existing methods aim at generating an interception posture with a hierarchical distribution in time and space based on the predicted trajectory of the hypersonic vehicles. Future work can be aimed at

designing a more efficient and reliable multi-interceptor cooperative guidance law by identifying the middle and terminal guidance handover conditions of the interceptors without the information interaction and sharing among interceptors.

In general, direct collision is the most effective form of interception, and an interceptor that successfully targets a hypersonic vehicle can cause significant damage. Considering the case shown in Fig. 5, it is assumed that the speeds of the interceptors and hypersonic vehicle remain constant during their motion, and the two types of vehicles maneuver with normal acceleration a_M and a_T , respectively. The motion regions of the interceptors and hypersonic vehicle in 2D space can be represented as two sectors, and the boundaries of the sectors are the maneuvering trajectories of the two vehicle types with maximum normal accelerations $a_{M,Max}$ and $a_{T,Max}$, respectively.

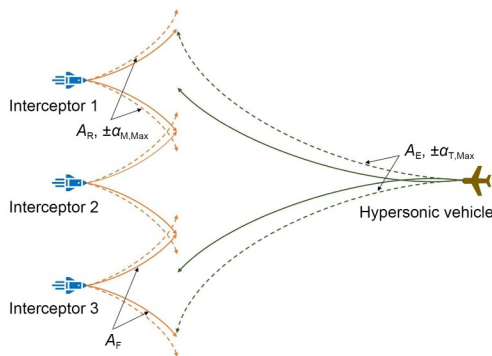


Fig. 5 Interception process based on the coverage strategy. A_R : reachable area; A_T : feasible area; A_E : escape area. Reprinted from (Liu et al., 2022b), Copyright 2022, with permission from Elsevier

In this interception scenario, we assume that no communication network exists among the interceptors. To increase the probability of multiple interceptors intercepting a hypersonic vehicle, the position and leading angle at the initial moment of the terminal guidance of the interceptors can be optimized, such that the interception area of each interceptor is split against the maneuvering area of the hypersonic vehicle (Liu et al., 2022b). On this basis, the guidance laws for the interceptors can be designed in such a way that each interceptor can effectively intercept part of the maneuvering area of the hypersonic vehicle. In this manner, regardless of the hypersonic vehicle's maneuvering modes, at least one interceptor can successfully intercept it. Therefore, a multi-interceptor cooperative

interception posture can be achieved with regard to spatial distribution (Fig. 6).

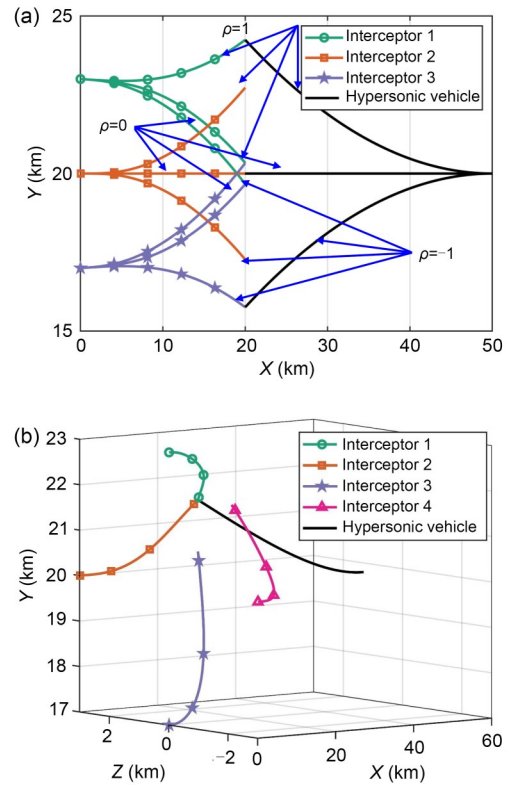


Fig. 6 Cooperative guidance based on the space domain: (a) 2D scenario (ρ is a ratio between the actual maneuverability and maximum maneuverability of the hypersonic vehicle) (Reprinted from (Liu et al., 2022b), Copyright 2022, with permission from Elsevier); (b) 3D scenario (Reprinted from (Liu et al., 2022f), Copyright 2022, with permission from Elsevier)

4.3 Design based on the physical domain

At the physical level, interceptors can be distinguished by their function, that is, by the source component of the detection information. Interceptors equipped with the same type of equipment are distinguished by their performance, mainly in terms of physical constraints such as the field-of-view of the guidance head that determines the detection range of the interceptor and the rudder-deflection angle that determines maneuverability. Interceptors with different types of equipment have different capabilities and can complement each other's performance, giving them a quantitative advantage. Therefore, the aspects of cooperation and competition within an interceptor group must be considered in future work. Specifically, the relationship

between cooperation and competition must be balanced to fully exploit the advantages of heterogeneous formations and accurately intercept hypersonic vehicles.

For example, the guidance head is a key component for obtaining information regarding the target's motion and achieving precise guidance. However, the installation of a guidance head increases the cost of an interceptor and decreases the space and weight capacity available for the payload. Moreover, robust design constraints are imposed by the harsh operating-environment requirements of the guidance warhead. Under the framework of cooperative guidance, heterogeneous interceptors with different functions can be used for cluster networking. In this scenario, only a few interceptors are equipped with guidance heads and communication chains among interceptors are used to share detection information. This framework can decrease the weight and size of the interceptors, narrow the scope of load-design constraints, and achieve functional complementarity and efficient cooperation among heterogeneous interceptors to enable refined, efficient, and multi-layered cooperative strikes on the battlefield of the future, as well as increasing the attack efficiency and battlefield adaptability of the interceptor group. This cooperative guidance mode is not bound by multi-agent consensus protocols and can effectively adapt to the complex mission requirements of multifunctional payloads on existing, mature carrier platforms, while shortening the interceptor development cycle and facilitating rapid development of operational capabilities.

As shown in Fig. 7, the interceptors in a heterogeneous interceptor group can be divided into detection and attack interceptors. Detection interceptors are designed for reconnaissance, detection, and assessment of the maneuvering areas of hypersonic vehicles.

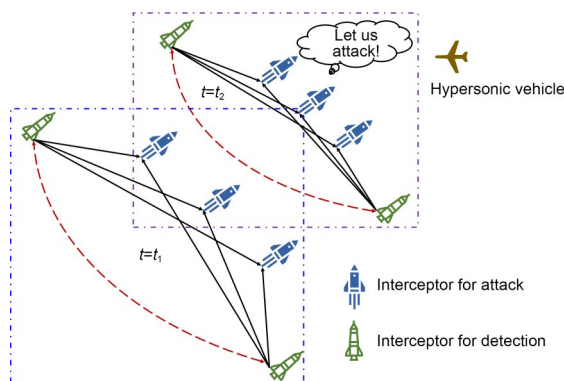


Fig. 7 Cooperative detection and guidance of heterogeneous interceptors

Attack interceptors are designed to precisely intercept hypersonic vehicles. Two detection interceptors mounted with guidance heads are the first to arrive on the battlefield. They reconnoiter the hypersonic vehicles and perform rapid coordinated detection (at the instant t_1). The obtained detection information is transferred to the attack interceptors without guidance heads, which arrive later. The attack interceptors use an information fusion algorithm to estimate target position and speed, and filter algorithms to extract information regarding their own angular velocity relative to that of the hypersonic vehicles (Waldmann, 2002). Subsequently, these interceptors precisely intercept the hypersonic vehicles (at the instant t_2). Finally, the detection interceptors conduct efficiency assessments after interception and transmit the data back via satellite communication, thereby completing the integrated operational process of reconnaissance, attack, and assessment.

4.4 Design based on effect-cost ratio

For a given hypersonic vehicle, multi-interceptor cooperative interception can generate a many-to-one interception posture, thereby increasing the kill and saturation attack probabilities. However, most of the existing multi-interceptor cooperative guidance laws operate on the cooperative guidance level and focus on achieving accurate interception of the target. These techniques do not clarify the number of interceptors required or the mode of cooperative operation. Simply increasing the number of interceptors may lead to increased interference of the motion state, increased operational cost, and reduced effect, despite investment of twice the effort. These aspects limit the engineering application value of cooperative guidance.

Furthermore, the existing multi-interceptor cooperative guidance laws require the use of multiple hypersonic interceptors to intercept a single hypersonic vehicle (Hui et al., 2015; Zhao et al., 2016; Tan et al., 2019). The interceptors must also be able to rapidly accelerate and decelerate (Zhou et al., 2016; You and Zhao, 2020), and the overload may be 30g or higher (Song et al., 2017; Yang et al., 2020). These aspects increase both the economic and the operational costs of the interceptors. Consequently, the number and speed of interceptors must be optimized along with the required overload and other performance indexes to achieve heterogeneous multi-interceptor cooperative guidance with guaranteed interception accuracy.

Future battlefield environments are expected to involve system-to-system confrontation. In the context of intercepting hypersonic vehicles, the attack effect of $1+1>2$ can only be achieved by ensuring interception accuracy and optimizing the number of interceptors and the performance index. Such frameworks can help ensure that each interceptor is used to its maximum capability, and that its battlefield value is fully exploited to balance the operational cost and battlefield response.

5 Conclusions

Hypersonic vehicles exhibit excellent concealment and surprise-defense capabilities, allowing them to surpass existing defense systems. The emergence of hypersonic vehicles has disrupted the balance of existing offensive and defensive systems. This review systematically summarizes the advantages of hypersonic vehicles and the difficulties in intercepting them. We covered the existing terminal guidance laws for intercepting hypersonic vehicles, based on the number of interceptors. With regard to these performance advantages and the difficulties in intercepting hypersonic vehicles, we looked at the potential of four future technologies to facilitate multi-interceptor cooperative interception of hypersonic vehicles; we believe this paper will provide a useful reference for future research on near-space interceptor terminal guidance technologies.

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Author contributions

All authors: conceptualization; Shuangxi LIU, Xu ZHANG, and Binbin YAN: investigation; Shuangxi LIU, Wei HUANG, and Jie YAN: methodology; Shuangxi LIU: writing; Binbin YAN: funding acquisition.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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