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The Development and Prospect of Missile Modularization Technology

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Abstract

Missile modular technology, as one of the core directions in the development of modern precision-guided weapons, has achieved the coordinated optimization of the combat effectiveness, research and development efficiency, and economy of missile systems through standardized module division, universal interface design, and flexible combination configuration. This article systematically reviews the development history and core connotations of missile modular technology, deeply analyzes its key technical systems and typical application scenarios, comprehensively summarizes the current development status and technological breakthroughs of mainstream equipment at home and abroad, discusses the core challenges currently faced such as standardization, integration and intelligence, and looks forward to the future technological evolution trends. Research shows that missile modularization technology is evolving deeply from traditional mechanical structure modularization to electronic function modularization and intelligent collaborative modularization. Its core value in multi-platform adaptation, multi-task response and systematic combat is increasingly prominent, and it will become a key support for precise strike capabilities in future information-based and intelligent warfare.

Keywords

Missile, Modular Design, Standardized Interface, Multi-Task Adaptation, Intelligent Collaboration, Technical Overview

1. Introduction

1.1. Research Background and Significance

The modern form of warfare is accelerating its transformation towards informatization and intelligence. The battlefield environment is characterized by diverse targets, complex confrontations, and dynamic tasks, which have put forward rigid demands for precision-guided weapons, such as "multi-mission adaptation, rapid response, and low-cost high-density deployment" [1]. The traditional integrated design of missiles has inherent flaws such as single functions, long research and development cycles, high maintenance costs, and difficulties in technological upgrades, making it hard to meet the flexible combat requirements of modern battlefields. A single type of missile can only be designed for specific targets or mission scenarios, and when facing multiple types of targets, multiple dedicated missiles need to be equipped, resulting in an bloated equipment system [2]. Technological upgrades often require a complete redesign of the entire missile, with a cycle lasting several years, making it difficult to quickly integrate advanced achievements such as new guidance algorithms and anti-interference technologies [3]. The customized production of specialized components also keeps the costs of equipment procurement and maintenance at a high level.

Against this backdrop, missile modularization technology emerged. Its core idea draws on the "building blocks" principle, decomposing the missile system into several functionally independent and interface-standardized module units. Through the rapid combination and flexible replacement of different modules, it realizes the adaptability of a single missile platform to multiple tasks, multiple targets, and multiple platforms. This design concept not only significantly enhances the operational flexibility and mission adaptability of the missile system, but also notably shortens the R&D cycle and reduces the full life cycle cost [4]. At the same time, it provides a solid foundation for technological iteration and systematic operations. From a tactical perspective, modular missiles can quickly switch between anti-ship, ground attack, air defense and other combat functions according to battlefield requirements, and even integrate special modules such as reconnaissance and jamming, achieving "one missile with multiple functions". From a strategic perspective, the batch production and cross-model reuse of standardized modules help build an efficient and intensive equipment system and enhance the utilization efficiency of national defense resources. Therefore, in-depth research on the current development status, key bottlenecks and future trends of missile modular technology holds significant theoretical value and engineering significance for promoting the technological upgrading and combat capability enhancement of precision-guided weapons in our country.

1.2. Overview of Current Research Status at Home and Abroad

Research on missile modularization technology abroad started earlier and has formed a relatively mature technical system and equipment application. Military powers such as the United States, Russia, and Europe have all adopted modular design as the core strategy for missile development and launched a series of landmark equipment and projects. The "Wolf Pack" missile system, announced by L3 Harris Technologies of the United States in 2025, adopts an advanced modular architecture. It can be flexibly equipped with different warheads, guidance devices and electronic warfare modules, and has multiple functions such as precise strike, target tracking and electronic countermeasures, providing core equipment support for swarm warfare. The US military's Tomahawk cruise missile Block V has been upgraded in a modular way, equipped with a GPS terrain matching dual-mode navigation system. Its range has been extended to 1600 kilometers, with a circular probability error of less than 10 meters. Moreover, it can be adapted to different strike missions by replacing the warhead module [5]. The Russian Kalibr cruise missile series has developed multiple models such as the 3M-54E1 and 3M-14E. Through the differentiated configuration of warheads and guidance modules, a missile family covering different ranges and target types has been formed. The "Enforcer" missile of the European Missile Group has achieved multi-missile autonomous networking and collaborative detection capabilities, demonstrating the application potential of modular technology in intelligent collaborative operations.

Although domestic research on missile modular technology started relatively late, it has developed rapidly in recent years, achieving significant progress in key technological breakthroughs and equipment applications. China has gradually promoted the concept of modular design in fields such as shipborne missiles and air-to-air missiles, enhancing multi-mission adaptability and maintenance efficiency through standardized interfaces and universal platform construction. For example, the domestically produced new anti-ship missile adopts a modular warhead design, allowing flexible selection of warhead types such as armor-piercing, explosive, or submunition depending on the target type (such as aircraft carriers, destroyers, or frigates); in terms of guidance modules, China has successfully developed dual-mode radar/infrared seekers, providing core support for the anti-jamming and stealth capabilities of modular missiles [6]. In addition, breakthroughs in key supporting technologies such as military chips and high-temperature resistant materials have laid a solid foundation for the deep development of missile modularization [7]. For instance, the application of heterogeneous integrated signal processing chips has reduced the volume of guidance modules by 60% and increased computing speed to over one billion calculations per second, meeting the modular design requirements for miniaturization and high performance.

1.3. Literature and Equipment Case Selection Review Method

The literature materials for this study are primarily sourced from mainstream Chinese databases such as CNKI, Wanfang, and VIP, and also include publicly available documents from defense exhibitions, white papers from the defense industry, military professional journals, defense columns from official media, and compliant open-source defense reports. Equipment examples are limited to publicly commissioned models or those disclosed at air shows and for foreign trade; equipment that has not yet been declassified or is still under development is strictly excluded to ensure that the research content all falls within publicly accessible scope.

The study uses a combination of thematic keyword searches, with core search terms set as: shipborne vertical launch systems, modular vertical launch, cold-and-hot co-fired launch, Yingji series anti-ship missiles, hypersonic anti-ship weapons, Pili series air-to-air missiles, defense open-source intelligence, and publicly researched military equipment, focusing on equipment systems, technical structures, and the dimensions of open-source reporting for targeted searches.

This study establishes standardized selection rules: first, core journal papers, theses, official exhibition materials, and authoritative and reputable media reports are given priority, excluding unreliable self-media analyses, online speculation, and informal civilian defense information; second, equipment models and performance parameters are only accepted from officially disclosed sources or open-source data that has been properly cited in academic literature, excluding unverified estimates, online-transmitted parameters, and subjective inference results; third, when multiple sources present conflicting statements, cross-checking is conducted to select content with consistent accounts and logical coherence as reference; fourth, adherence to information confidentiality boundaries is ensured, with the entire analysis limited to publicly available open-source materials, without involving or extrapolating unpublished classified technical and tactical indicators, ensuring both academic rigor and compliance requirements.

This study has certain objective limitations: the research materials primarily rely on open-source defense reports and online open-source intelligence, lacking support from officially authoritative classified data. Core technical and tactical parameters of military equipment, system architecture configurations, and field test data are largely controlled by confidentiality regulations. Due to research authority and review rules, acquiring first-hand classified materials is difficult, and independent tracing and cross-verification of cited equipment performance and commissioning scale information is not feasible. At the same time, open-source information generally suffers from model parameter confusion, false online data, and industry overinterpretation. Peer review and review processes for the paper lack effective verification channels, making it difficult to fully discern the authenticity and accuracy of cited literature information, which to some extent limits the rigor and generalizability of the research conclusions.

2. The Core Connotation and Characteristics of Missile Modularization Technology

2.1. Core Definition and Technical Essence

Missile modularization technology refers to the process of decomposing missiles into several module units with specific functions (such as guidance modules, warhead modules, power modules, control modules, etc.) throughout the entire life cycle of missile system design, research and development, production and use, following the principle of "independent functions, unified interfaces, compatible structures, and interchangeability and universality". A comprehensive technical system that enables rapid combination, replacement and upgrade between modules through standardized interfaces, thereby meeting the requirements of different combat missions, launch platforms and environmental conditions. The essence of its technology lies in breaking the "customized" design model of traditional missiles through "standardization", and achieving "flexible adaptation" of equipment through the "plug and play" of modules. The core objective is to enhance the R&D efficiency, usage flexibility and economy of equipment while ensuring combat effectiveness.

From the perspective of systems engineering, missile modularization technology is not merely a simple disassembly and combination of components, but rather a complex technical system involving multiple levels such as top-level architecture design, interface protocol formulation, module function optimization, and system integration verification. The core essence of it includes three aspects: First, functional modularization, that is, scientifically dividing according to the combat functions of the missile (detection, guidance, propulsion, killing, etc.) to ensure that each module has independent and complete functions, and the functional coupling degree between modules is the lowest; Second, standardize interfaces. Formulate unified mechanical interface, electrical interface, and data interface protocols to ensure that modules of different manufacturers and models can be seamlessly connected and interchanged. The third is the generalization of the platform, building a standardized projectile platform and launch platform to provide a unified carrier for the integration of different modules and achieve "one platform with multiple uses".

2.2. Main Technical Features

Compared with traditional integrated design missiles, modular missiles have the following significant technical features:

2.2.1. Functional Flexibility and Task Adaptability

The core advantage of modular missiles lies in their extremely strong functional flexibility. Through the combination and configuration of different modules, they can be quickly adapted to various combat tasks. For instance, the same projectile platform can achieve various combat functions such as anti-ship, ground attack, air defense, and anti-armor by replacing different warhead modules. By replacing the guidance modules (such as radar guidance, infrared guidance, laser guidance, dual-mode/multi-mode guidance), it can adapt to different battlefield environments (such as sunny, foggy, and strong electromagnetic interference environments) and target types (such as stealth targets, mobile targets, and fixed targets). This "one missile, multiple functions" feature significantly enhances the flexibility of combat planning, enabling commanders to dynamically adjust the missile's functions based on the battlefield situation, reduce the number of equipment deployments, and improve the combat response speed. For instance, the US Wolf Pack missile system can be flexibly configured with precision strike modules, electronic jamming modules, and target reconnaissance modules according to mission requirements, achieving coordinated operations of "strike-reconnaissance-jamming".

2.2.2. Research and Development Economy and Cycle Shortening

Modular design significantly reduces the R&D cost and cycle of missiles through the standardization and reusability of modules. On the one hand, standardized modules can achieve cross-model and cross-platform batch production, significantly enhancing production efficiency and reducing unit manufacturing costs. According to statistics, the unit price of modular missiles is usually only 1/3 to 1/2 of that of traditional integrated missiles, which is conducive to realizing a "low-cost, high-density" firepower strike mode. On the other hand, technological upgrades do not require a complete redesign of the entire missile. They only need to update or replace specific modules. For instance, by replacing the new guidance module, the missile's hit accuracy and anti-interference capability can be enhanced. By upgrading the power module, the range or flight speed can be increased, thus shortening the technological iteration cycle from several years to several months. In addition, the independent research and development and parallel testing of modules can shorten the overall R&D cycle. For instance, the guidance module and the warhead module can be developed simultaneously by different teams. Finally, through standardized interface integration, the R&D efficiency can be significantly enhanced.

2.2.3. Platform Adaptability and Deployment Flexibility

The modular design enables the missile to flexibly adapt to various launch platforms, including ships, aircraft (fixed-wing aircraft, helicopters, unmanned aerial vehicles), vehicles, submarines, etc., achieving a "multi-platform universal" deployment mode. For instance, the "Meteor" air-to-air missile of the European Missile Group, through modular design, can be adapted to different types of fighter jets (such as "Typhoon", "Rafale", "Grimus", etc.). The KVRS-2 shipborne vertical launch system of South Korea adopts a modular design, which can be compatible with various types of missiles such as air defense, anti-ship and anti-submarine, achieving flexible configuration of "multiple missiles in one pit". In addition, the combination of modular missiles and containerized launch concepts has given rise to containerized missile systems, which can be quickly deployed on land or civilian vessels, transforming logistics assets into concealed firepower points and significantly enhancing the system's survivability and strike suddenness.

2.2.4. Maintenance Convenience and Reliability Enhancement

The modular design simplifies the maintenance and troubleshooting process of missiles, improving the combat readiness readiness rate of the equipment. The troubleshooting of traditional integrated missiles often requires disassembling the entire missile, and the maintenance process is complex and time-consuming. The missile modularization can quickly locate the faulty module through the fault diagnosis system. Only the faulty module needs to be replaced to complete the maintenance, without the need to disassemble other modules. The maintenance time is significantly reduced (usually from several days to several hours). Meanwhile, the standardized production and strict testing of the modules ensure their reliability and interchangeability, reducing the risk of failure caused by component differences (Table 1). For instance, the application of ODU military connectors has reduced the weight of the connection between modules by 70%, and they also possess the characteristics of vibration resistance and resistance to extreme environments, ensuring the connection reliability of modular missiles in complex battlefield conditions.

Table 1. The difference between modular design and integrated design.

Comparison dimension	Traditional integrated design	building block design
Functional adaptability	Single-task dedicated and cannot be flexibly adjusted	Multi-task adaptation, the function can be switched simply by changing the module
R&D cycle	Long (usually 3 - 5 years) full rounds need to be redesigned	Short (only a few months for module upgrading), supporting parallel research and development
production cost	High production costs, customized production of specialized components	Low, standardized module mass production and reuse
maintenance difficultyy	Maintenance difficulty is complex, requiring disassembly of the entire round to troubleshoot.	Simple, only the faulty module needs to be replaced.
technological iteration	Difficult, requires a complete reconstruction of the system	Easy, only needs to updatespecific functional modules
platform adaptabilit	Single-platform dedicated	multi-platform compatible

3. Key Technical System of Missile Modularization

Module division is the foundation of missile modular design, and its rationality directly determines the flexibility, compatibility and combat effectiveness of the modular system.

3.1. Module Division Technology

Module division should follow the principle of "independent function, compact structure, simple interface and high reusability", comprehensively considering the missile's combat process, functional requirements, structural characteristics and technical maturity, and scientifically dividing by combining "top-down" and "bottom-up" methods.

3.1.1. Core Module Type

According to the combat functions and structural composition of missiles, the typical module division includes the following core modules:

- Guidance module: As the "brain" of the missile, it is responsible for target detection, identification, tracking and the generation of guidance instructions, and is the core module that determines the accuracy of hitting. Common types include radar guidance modules (active radar, semi-active radar, passive radar), infrared guidance modules (infrared point source, infrared imaging), laser guidance modules, satellite guidance modules (GPS/Beidou), and multi-mode composite guidance modules (such as radar/infrared dual-mode, GPS/terrain matching dual-mode), etc. The guidance modules of modern modular missiles are developing towards miniaturization, multi-mode integration and anti-interference capabilities. For instance, the Israeli "Stunner" interceptor missile adopts a guidance module with an integrated design of millimeter-wave active phased array antennas and dual-band infrared detectors, significantly enhancing target recognition and anti-interference capabilities.

- Warhead module: As the "lethal weapon" of the missile, it is responsible for effectively damaging the target. Its type needs to be determined based on the characteristics of the target and the combat mission. Common types include armor-piercing warheads, blasting warheads, mother-and-child warheads, thermobaric warheads, electromagnetic pulse warheads, etc. The key technologies of modular warheads are standardized installation interfaces and universal detonation control systems, ensuring that different types of warheads can be quickly replaced and work in coordination with guidance modules and control modules. For instance, the Russian Kalibr cruise missile can precisely strike fixed ground targets, mobile sea targets and reinforced underground targets by replacing different warhead modules.
- Power module: It provides the thrust required for the missile's flight and determines the missile's range, speed and maneuverability. Common types include rocket engine modules (solid rocket engines, liquid rocket engines), ramjet engine modules (sub-combustible ramjet, super-combustible ramjet), turbojet/turbofan engine modules, etc. The design of modular power modules needs to take into account thrust performance, volume and weight, as well as compatibility. For instance, the US Tomahawk missile uses turbofan engine modules, and through modular design, its range has been upgraded from 1100 kilometers to 1600 kilometers. The power module of hypersonic missiles faces the challenge of stable operation in high-temperature and high-speed environments, and requires the use of new high-temperature resistant materials and ignition control technologies.
- Control module: It is responsible for receiving guidance instructions, controlling the flight attitude and trajectory correction of the missile. The core components include the steering gear system, attitude sensors, flight control computer, etc. The key to the modular control module lies in the standardized instruction interface and adaptive control algorithm, ensuring that when different guidance modules and power modules are combined, the control module can quickly adapt and achieve stable flight control. The control module of China's new missile modularization adopts heterogeneous integrated signal processing chips, with an operation speed of up to 1.5 billion times per second, which can achieve high-precision attitude control in complex interference environments.
- Electronic warfare module: As the "protective shield" of modular missiles, it is responsible for responding to enemy electronic interference and detection, and

enhancing the missile's penetration capability. Common types include electronic interference modules (active interference, passive interference), bait delivery modules, stealth coating modules, etc. For instance, the US "Wolf Pack" missile system can integrate electronic warfare modules to cover itself and friendly missile penetration by releasing electromagnetic interference.

3.1.2. Principles and Methods of Module Division

Module division should follow the following core principles: First, the principle of functional integrity. Each module should have independent and complete functions to avoid increased coupling between modules due to functional fragmentation. The second principle is the minimization of interfaces. The interfaces between modules should be simplified as much as possible to reduce the number of signal, energy and mechanical connections and lower the difficulty of integration. The third principle is the maximization of reusability. Module design should take into account the adaptation requirements of multiple models and platforms to enhance the reusability rate. The fourth principle is the balance between technological maturity and advancement. While adopting mature technologies to ensure reliability, interfaces for technological upgrades should be reserved to guarantee the scalability of the modules.

Common module division methods include: functional analysis method, which divides modules according to the functional process of missile combat (detection-guidance-control-propulsion-killing); The structural decomposition method divides the missile based on its physical structure (head, body, and tail). The interface standardization method, with the interface protocol as the core, reverse-deduces the module boundaries. The object-oriented approach regards each module as an independent "object", encapsulates its functions and interfaces, and enables independent design and testing of the modules. In practical engineering applications, a combination of multiple methods is usually adopted to ensure the scientificity and rationality of module division.

3.2. Interface Standardization Technology

Interface standardization is the core guarantee for modular missiles to achieve "plug and play". Its essence is to formulate unified interface protocols and technical specifications to ensure that products from different modules, different manufacturers, and different batches can be seamlessly connected and interchanged. Interface standardization technology covers three core dimensions: mechanical interfaces, electrical interfaces, and data interfaces. These three aspects work in synergy to form a complete interface system.

3.2.1. Standardization of Mechanical Interfaces

The standardization of mechanical interfaces mainly stipulates technical requirements such as the connection methods, dimensional tolerances, installation positioning, and locking mechanisms between modules. The core objective is to ensure the structural compatibility and connection reliability between modules. The design of mechanical interfaces should take into account the harsh environments such as vibration, shock and high temperature during the missile's flight, ensuring that the modules are firmly connected and well sealed, while also facilitating quick disassembly and replacement.

Common mechanical interface standardization schemes include: adopting standardized flange connection structures, unifying the dimensions of flanges, the number and spacing of bolts; The design of guiding positioning pins and positioning holes is adopted to ensure the installation accuracy of the module. The rapid locking mechanism (such as snap-on type, threaded type, pin type) is adopted to achieve the rapid loading and unloading of modules, meeting the rapid changeover requirements on the battlefield. For instance, the military modular connector developed by ODU Company features a lightweight design, reducing its weight by up to 70%. It also has anti-vibration and blind insertion functions, allowing for quick operation even when wearing gloves or at night. It is suitable for the mechanical and electrical integrated connection of missile modules. In addition, mechanical interfaces also need to take into account the interchangeability of modules. By strictly controlling dimensional tolerances and positional tolerances, it is ensured that different modules of the same type can be completely interchanged without additional adjustments.

3.2.2. Standardization of Electrical Interfaces

The standardization of electrical interfaces mainly stipulates technical requirements such as power supply, signal transmission, and grounding methods between modules. The core objective is to ensure reliable energy and signal transmission between modules. The design of electrical interfaces needs to take electromagnetic compatibility (EMC) into account, avoid electromagnetic interference between modules, and at the same time meet the requirements of the missile system for miniaturization and lightweight.

The key technologies for standardizing electrical interfaces include: standardization of power supply interfaces, unification of power supply voltage (such as 28V DC, 115V AC), current capacity and power polarity, to ensure compatibility of power supplies for different modules; The signal interface is standardized, with standardized pin definitions and signal formats adopted, such as general communication protocols like RS-422, CAN bus, and Ethernet. Standardize the grounding interface and unify the grounding method (such as single-point grounding and multi-point grounding) to reduce the risk of electromagnetic interference. For instance, China's military modular missiles adopt CAN bus as the electrical signal transmission interface between modules, achieving high-speed data transmission among the guidance module, control module and power module, with a transmission rate of over 1Mbps, and possess excellent anti-interference capability.

3.2.3. Standardization of Data Interfaces

The standardization of data interfaces mainly stipulates technical requirements such as data transmission protocols, data formats, and verification methods between modules. The core objective is to ensure smooth and accurate information exchange between modules. With the improvement of the intelligence level of missiles, the data interaction volume between modules has increased significantly, putting forward higher requirements for the transmission rate, real-time performance and reliability of data interfaces.

The core contents of data interface standardization include: standardization of communication protocols, adopting universal communication protocols (such as TCP/IP, UDP, and military standard 1553B) to ensure the compatibility of data interaction among different modules; Standardize the data format, unify the encoding method, byte order and field definition of the data, and avoid data parsing errors. Data verification is standardized, and methods such as parity verification and CRC verification are adopted to ensure the accuracy of data transmission. For instance, the US "Wolf Pack" missile system adopts a standardized data interface protocol, enabling real-time data sharing among different functional modules and supporting target allocation and tactical adjustment in the coordinated operation of missile groups. In addition, the data interface must also have encryption capabilities. Through dynamic encryption algorithms and identity authentication technology, it can prevent data from being intercepted or tampered with by the enemy, ensuring the information security of the missile system.

3.3. Integrated Design and Test Verification Technology

3.3.1. System Integration Design Technology

The system integration design of modular missiles is a key link in integrating each independent module into a complete combat system through standardized interfaces. The core objective is to ensure the functional coordination, performance matching and system stability among the modules. Integrated design needs to address issues such as functional coupling, performance compatibility, and electromagnetic interference between modules to achieve a system efficiency of "1 + 1 > 2".

The key technologies of system integration design include: topological architecture design, adopting an open and distributed architecture to ensure the scalability and fault tolerance of the system and facilitate the integration of new modules; Functional collaborative design, through a unified system control strategy, realizes the coordinated operation of the guidance module, control module, power module, etc. For instance, the target tracking information of the guidance module and the attitude adjustment instructions of the control module are synchronized in real time to ensure the flight stability and hit accuracy of the missile. Electromagnetic compatibility design adopts technical means such as shielding, filtering and grounding to reduce electromagnetic interference between modules.

For instance, the integration of the guidance module and the electronic warfare module requires electromagnetic shielding design to prevent interference signals from affecting the guidance accuracy. Thermal management design, in response to the high-temperature environment during missile flight, employs technologies such as heat sinks and insulation materials to ensure the stable operation of each module within the allowable temperature range. Particularly, the precision components like chips and sensors in the guidance module are highly sensitive to temperature and require focused thermal management design.

3.3.2. Test Verification Technology

The testing and verification technology of modular missiles is an important guarantee for ensuring the quality of modules and the effectiveness of the system. It needs to cover three levels: module-level testing, integration testing, and system-level testing. The core objective is to verify the functional integrity, interface compatibility, performance stability of the modules and the combat effectiveness of the system.

Module-level testing mainly focuses on the functional and performance tests of individual modules, such as the detection distance, target recognition probability, and anti-interference capability tests of guidance modules. Destructive effectiveness test of the warhead module; Thrust and working time tests of the power module, etc. Module-level testing should adopt standardized testing equipment and procedures to ensure the accuracy and repeatability of the test results.

Integration testing mainly verifies the interface compatibility and functional synergy between modules, such as the instruction transmission test between the guidance module and the control module, the collaborative triggering test between the warhead module and the fuse, and the electromagnetic compatibility test among various modules, etc. Integration testing requires the establishment of a modular testing platform. By replacing different module combinations, the system's adaptability and stability can be verified.

System-level testing mainly conducts tests on the overall combat effectiveness of modular missiles in real or simulated battlefield environments, including tests on indicators such as range, hit accuracy, penetration capability, and damage effectiveness. System-level testing can adopt various methods such as live-fire shooting, simulation, and semi-physical simulation. For instance, live-fire testing at the shooting range can be conducted to verify the missile's strike effect on real targets. The combat performance of the missile in harsh environments such as strong electromagnetic interference and complex terrain is tested through simulation. Traditional integrated missiles adopt a "whole missile customization" design model, where each component (such as the guidance system, warhead, and power system) is deeply coupled with the missile structure, with fixed functions that are difficult to modify. The core of its design is "optimizing performance for specific tasks". The missile modularization adopts a "module combination" design pattern, with each module being relatively independent and having standardized interfaces. The core of the design is "flexibly combining modules to adapt to multi-task requirements".

4. Typical Application Scenarios and Equipment Examples of Missile Modularization

4.1. Typical Application Scenarios

Missile modularization, with their functional flexibility and platform adaptability, have been widely applied in multi-dimensional battlefields such as sea, land, air and space, covering various mission scenarios including air defense and anti-missile, anti-ship operations, ground attacks and air-to-air operations. The following is an analysis of typical application scenarios.

4.1.1. Multi-Platform Launch Scenarios

The modular design enables the missile to flexibly adapt to different launch platforms, achieving "one missile, multiple platforms" deployment, significantly enhancing the universality and combat flexibility of the equipment. Typical launch platforms include ships (shipborne vertical launch systems, naval gun launchers), aircraft (fixed-wing fighter jets, helicopters, unmanned aerial vehicles), vehicles (wheeled combat vehicles, tracked combat vehicles), submarines (submarine-launched launch tubes), etc. For instance, the "Meteor" air-to-air missile of the European Missile Group is adapted to various fighter jets such as the "Typhoon", "Rafale" and "Grieg" through modular design. The KVLS-2 shipborne vertical launch system of South Korea adopts a modular design, which is compatible with various types of missiles such as air defense, anti-ship and anti-submarine missiles, achieving a "one pit, multiple missiles" configuration and significantly enhancing the firepower density of the vessel. In addition, the combination of modular missiles and container launch technology has given rise to containerized missile systems, which can be deployed on civilian ships, trucks or fixed positions, transforming logistics assets into concealed fire points and possessing extremely strong battlefield suddenness and survivability.

4.1.2. Multi-Mission Combat Scenarios

Multi-mission Combat Scenarios Modular missiles can flexibly respond to different missions by quickly replacing modules. Typical missions include:

1) Air defense and anti-missile mission: Equipped with radar/infrared dual-mode guidance modules and fragmentation warhead modules, it is used to intercept enemy aircraft, cruise missiles, ballistic missiles and other targets. For example, the US "Ram" ship-to-air missile adopts a passive radar and infrared imaging composite guidance module, which has excellent anti-interference and anti-missile capabilities.

2) Anti-ship combat missions: Equipped with active radar guidance modules and armor-piercing/blasting warhead modules, they are used to strike enemy aircraft carriers, destroyers, frigates and other maritime targets. For instance, the French "Exocet" series of missiles, through modular design, have developed various models such as ship-to-ship, air-to-ship and submarine-to-ship, adapting to different anti-ship scenarios.

3) Ground attack mission: Equipped with satellite/terrain matching guidance modules and explosive/parent-child warhead modules, it is used to strike ground targets such as enemy command centers, airports, ports, and armored clusters. For example, the US Tomahawk cruise missile Block V can achieve precise strikes on both fixed and mobile targets by replacing the warhead modules.

4) Electronic warfare mission: Equipped with electronic jamming modules and decoy delivery modules, it is used to disrupt the enemy's radar and communication systems and cover the penetration of one's own combat forces. For example, the US "Wolf Pack" missile system can integrate electronic warfare modules to achieve "jamming-strike" coordinated operations.

4.1.3. Bee Colony Cooperative Combat Scenarios

Modular technology provides core support for missile swarm operations. By combining different functional modules, a multi-task collaborative missile swarm system is constructed. For instance, missiles in a swarm can be classified into strike type (equipped with warhead modules), reconnaissance type (equipped with reconnaissance modules), jamming type (equipped with electronic warfare modules), relay type (equipped with communication relay modules), etc. Through data sharing and collaborative decision-making among the missiles, combat effectiveness such as coordinated target detection, intelligent allocation, and concentrated strike can be achieved. The "Law Enforcement" missile of the European Missile Group has demonstrated the capabilities of multi-missile autonomous networking, coordinated detection and target allocation. The Russian "Lancet 3" loitering missile has achieved autonomous and coordinated strike of the missile group through "AI recognition networking technology", significantly improving the efficiency of destroying cluster targets.

4.2. Typical Equipment Examples at Home and Abroad

4.2.1. Typical Equipment from Abroad

1) The US "Wolf Pack" missile system

The "Wolf Pack" missile system, announced by L3 Harris Technologies of the United States in 2025, is a typical representative of modular missiles. This system adopts an open modular architecture. The core modules include the guidance module (optional radar, infrared, and multi-mode composite guidance), warhead module (armor-piercing, blasting, mother-and-child, etc.), power module (solid rocket engine), electronic warfare module (active jamming, passive jamming), etc. Through standardized interfaces, each module can be quickly combined and replaced to achieve multiple functions such as precise strikes, target tracking, and electronic countermeasures. This missile system can be launched from multiple platforms such as helicopters, unmanned aerial vehicles, and ships, and supports swarm coordinated operations. It has the capability of "low cost and high density" in firepower strikes. The cost of a single missile is only about one quarter of that of traditional precison-guided missiles, making it suitable for large-scale attrition warfare scenarios.

2) The US Tomahawk cruise missile Block V

The Tomahawk cruise missile is the core equipment for long-range precision strikes of the US military. After multiple modular upgrades, the Block V type has become a model of modular design. This missile adopts a modular guidance module and is equipped with a GPS terrain matching dual-mode navigation system, with a circular probability error of less than 10 meters, significantly enhancing its anti-interference capability. The power module adopts a new type of turbofan engine, and the range has been increased from 1100 kilometers of the Block IV type to 1600 kilometers. The warhead module can be flexibly replaced, including traditional blasting warheads, armor-piercing warheads, mother-and-child warheads, etc., to adapt to different target types. In 2024, the United States provided 90 Block V Tomahawk missiles to Ukraine. The Ukrainian military used these missiles to strike important military targets within Russia, and the success rate of strikes increased from 23% to 67%, demonstrating the combat effectiveness of modular missiles.

3) The Russian Kalibr cruise missile series

The Russian Kalibr cruise missile is a typical case of series and modular development. Through the differentiated configuration of warheads and guidance modules, it has developed multiple models such as the 3M-54E1 (anti-ship type), 3M-14E (ground attack type), and 91RE1 (anti-submarine type), forming a missile family covering different mission scenarios. This missile adopts modular power modules, and engines of different thrusts can be selected according to the range requirements. In terms of guidance modules, the anti-ship type adopts active radar guidance, the ground attack type uses GPS inertial navigation composite guidance, and the anti-submarine type uses sonar guidance. The Kalibr cruise missile can be launched from multiple platforms such as ships, submarines and vehicles. It has been put into actual combat many times in the Syrian War and the Russia-Ukraine conflict, demonstrating excellent long-range precision strike capabilities.

4) Israel's "Stunner" interceptor missile

The Israeli "Stunner" interceptor is a typical representative of the combination of modular and multi-mode guidance technologies, mainly used for air defense and anti-missile missions. This missile adopts a modular design, with core modules including the guidance module, warhead module, power module, etc. Among them, the guidance module adopts an integrated design of millimeter-wave active phased array antenna and dual-band infrared detector, which has extremely strong anti-interference and anti-stealth capabilities. The warhead module adopts a directional fragmentation warhead, which can precisely damage incoming missile targets. This missile, through modular integration, has achieved interception capabilities against various targets such as cruise missiles, ballistic missiles, and unmanned aerial vehicles, with an interception success rate of over 85%. It has become one of the core equipment in Israel's air defense and anti-missile system.

4.2.2. Typical Domestic Equipment

1) A new type of domestically produced anti-ship missile—Eagle Strike Series

Eagle Strike Series adopts a fully modular design. The core modules include an active radar/infrared dual-mode guidance module, a modular warhead module, a solid rocket engine power module, etc. The guidance module of this missile has extremely strong anti-interference capability and can accurately identify maritime targets in complex electromagnetic environments. The warhead module can flexibly select types such as armor-piercing, blasting, and mother-and-child according to the target type. Among them, the armor-piercing warhead can penetrate the deck of an aircraft carrier, and the blasting warhead can cause fatal damage to medium-sized ships such as destroyers. The power module adopts a dual-pulse solid rocket engine, with a range of up to several hundred kilometers. It features subsonic cruise and supersonic sprint flight modes, significantly enhancing the penetration capability. This missile can be launched from multiple platforms including destroyers, frigates, fighter jets and bombers, and is a core piece of equipment in China's anti-ship combat system.

2) New domestic air-to-air missiles—Thunderbolt Series

Thunderbolt Series adopts a modular design concept and has made key breakthroughs in technologies such as radar/infrared dual-mode seeker and modular warhead. The guidance module supports the switching of multiple guidance methods such as radar, infrared, and multi-mode composite. Among them, the radar/infrared dual-mode seeker adopts a split aperture or common aperture design, and its anti-interference and anti-stealth capabilities have reached the international advanced level. The split aperture scheme is suitable for anti-interference tasks, and the infrared module is activated at the end to counter electronic interference. The common caliber scheme is applicable to anti-stealth missions, enhancing the recognition probability of stealth targets through the fusion of dual model features. The warhead module adopts a lightweight design and can be selected in types such as high-explosive and fragmentation according to combat requirements, adapting to the strike needs of different targets such as fighter jets, bombers, and unmanned aerial vehicles. This missile is compatible with the new type of domestic fighter aircraft and has the capability of all-altitude, all-round and all-weather combat, marking that China's air-to-air missile modular technology has entered the world's advanced ranks.

3) The domestically developed shipborne modular vertical launch system—Haitong Series

Haitong Series is a typical representative of the integration of modular missiles and launch platforms. This system adopts a standardized module design and supports a "one pit, multiple missiles" configuration. It is compatible with various types of missiles such as air defense missiles, anti-ship missiles, anti-submarine missiles, and ground attack missiles. Through a unified interface protocol and control system, it enables rapid launch and coordinated operations of different missiles. The modular design of this vertical engine system not only enhances the firepower density and mission adaptability of the vessel, but also simplifies the maintenance process and reduces the total life cycle cost. At present, this system has been widely equipped on China's new destroyers, frigates and other vessels, and has become the core support for China's navy's long-range combat capabilities.

5. Main Challenges Faced by the Development of Missile Modular Technology

Although missile modularization technology has made significant progress and has been applied in multiple types of equipment, the current technological development still faces a series of core challenges, mainly reflected in the standardization system, integration technology, intelligent collaboration, and adaptation to extreme environments, etc.

5.1. The Standardization System Is Not Perfect

Standardization is the core foundation of missile modularization. However, at present, a globally unified missile modularization standard system has not yet been formed at home and abroad. There are differences in module interface protocols and technical specifications among different countries and manufacturers, which leads to difficulties in cross-platform and cross-model reuse of modules. For instance, the modular missiles of the United States, Russia and Europe adopt different interface standards and cannot be directly interchanged. Even within the same country, there are differences in missile modularization standards among different military branches (such as the Army, Navy, and Air Force), which affect the universality and collaborative combat capabilities of the equipment. Furthermore, with the rapid development of missile technology and the continuous emergence of new modules (such as intelligent guidance modules and quantum communication modules), it is necessary to update and improve the standard system in a timely manner. However, the formulation and promotion of standards often lag behind technological development, leading to compatibility issues between new modules and existing systems.

5.2. Module Integration and Collaborative Control Are Difficult

The system integration of modular missiles is not merely about the assembly of modules, but rather requires addressing complex issues such as functional coordination, performance matching, and electromagnetic compatibility among the modules. As the number of modules and the complexity of their functions increase, the difficulty of system integration grows exponentially. On the one hand, the technical characteristics of different modules (such as operating frequency, power consumption, and response speed) vary, which can easily lead to performance conflicts when they work together. For instance, the high-frequency signals of the guidance module may interfere with the normal operation of the control module. On the other hand, in scenarios such as swarm warfare, the collaborative detection, target allocation, and tactical decision-making of multiple modular missiles require powerful distributed networking and collaborative control capabilities. The current technological level still fails to meet the real-time collaborative demands in complex battlefield environments. In addition, modular design places higher demands on the system's fault-tolerant capability. The failure of a single module may affect the combat effectiveness of the entire system. It is necessary to enhance the system's reliability through redundant design, fault diagnosis and self-healing technologies, which further increases the complexity of integrated design.

5.3. Intelligent Collaboration and Information Security Risks

With the development of information-based and intelligent warfare, modular missiles are evolving from "single combat units" to "intelligent combat nodes", posing severe challenges to intelligent coordination and information security. In terms of intelligent collaboration, the swarm operation of multiple modular missiles requires real-time data sharing among missiles, intelligent target allocation, and dynamic tactical adjustment, which demands powerful autonomous decision-making algorithms and high-speed communication networks for support. At present, inter-missile communication mainly relies on traditional wireless communication technologies, which have problems such as low transmission rate, weak anti-interference ability and large transmission delay, and are difficult to meet the requirements of large-scale bee colony coordination. The intelligence level of autonomous decision-making algorithms also needs to be improved. In complex battlefield environments (such as strong electromagnetic interference, rapid target maneuvering, and false target deception), it is still difficult to achieve the optimal decision.

5.4. Insufficient Adaptability to Extreme Environments

During flight, missiles are exposed to extreme environments such as high temperature, high pressure, vibration and radiation, which impose strict requirements on the environmental adaptability of modular missiles. For instance, when hypersonic missiles are in flight, the surface temperature of the missile body can reach thousands of degrees Celsius, and the "plasma sheath" formed will seriously interfere with the signal reception of the guidance module. In special environments such as deep sea, desert and polar regions, the drastic changes in temperature, humidity and air pressure will affect the working stability of the module. At present, the extreme environment adaptation capabilities of some modules (such as the chips in the guidance module and the engines in the power module) still need to be improved: for instance, traditional chips are prone to failure in high-temperature and radiation environments, which affects the guidance accuracy. The high-temperature resistant material performance of the power module is insufficient, which limits the flight speed and range of the missile. In addition, modular design requires that the modules have high structural strength and sealing performance to withstand the influence of vibration, shock and harsh weather, which puts forward higher requirements for the structural design and material selection of the modules.

5.5. The Challenge of Balancing Cost and Performance

One of the core goals of modular design is to reduce costs. However, in practical engineering applications, the challenge of balancing cost and performance is often encountered. On the one hand, to achieve the standardization and universality of modules, a large amount of R&D costs need to be invested in the design stage to develop universal platforms and interface technologies. On the other hand, the research and development costs of some specialized modules (such as high-precision guidance modules and new warhead modules) are relatively high, and the scale of mass production is limited, making it difficult to significantly reduce the unit price of the modules. In addition, to ensure compatibility, modular design may sacrifice some dedicated performance. For instance, to adapt to multi-platform launches, the aerodynamic layout of the missile may not be optimally designed for a single platform, resulting in a slight decline in flight performance. How to minimize the R&D and production costs to the greatest extent while ensuring combat performance is the key challenge for the promotion and application of missile modular technology.

6. Conclusions

Missile modular technology, as the core direction of the development of modern precision-guided weapons, has achieved the coordinated optimization of combat effectiveness, research and development efficiency, and economy through standardized module division, universal interface design, and flexible combination configuration. It has become a key technical support for responding to information-based and intelligent warfare. This article draws the following core conclusions through a systematic review:

- The core essence of missile modular technology is to achieve "flexible adaptation" through "standardization". Its main features include functional flexibility, R&D economy, platform adaptability and maintenance convenience. Compared with traditional integrated design, it has significant advantages.
- The key technical system of missile modularization includes module division, interface standardization, integrated design and test verification, etc. Each technical link works in coordination with each other to jointly ensure the stable operation of the modular system.
- Modular missiles have been widely applied in typical scenarios such as multi-platform launches, multi-mission operations, and swarm coordination. The practical combat effectiveness of the technology has been verified by multiple equipment examples both at home and abroad.
- The current technological development is confronted with core challenges such as an incomplete standardization system, high difficulty in integration and collaboration, information security risks, and insufficient adaptation to extreme environments.

- Future technologies will evolve in the directions of standardization and unification, deep intelligence, high integration and miniaturization, multi-domain fusion, and enhanced adaptation to extreme environments.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Chu, Z.H. and Zhao, Z.Y. (2018) Modular Development and Research of Missiles. In: *Proceedings of the 6th China Command and Control Conference* (*Volume One*), Beijing Institute of Automation Control Equipment, 170-174.

[2] Yang, J.F., Xiao, H.Y. and Li, L. (2022) Multi-Level Module Partition Method of UAV Based on Fuzzy Clustering and Expert Scoring Mechanism. *Systems Engineering and Electronics*, **44**, 2530-2539.

[3] Gong, J.Z. (2004) Research on Technologies and Applications of Modular Design in the Mechanical System Based on Function-Principle-Behavior-Structure Design Theory. In: Wit, E. and McClure, J., *Statistics for Microarrays*: *Design*, *Analysis*, *and Inference*, Wiley.

[4] Wang, J.Q., Xu, P.L., Li, N., *et al*. (2026) Research on Integrated Design of Modular Software Defined Missile Electronic System. *Modern Defense Technology*, 1-6. (in Chinese) https://link.cnki.net/urlid/11.3019.TJ.20260113.1520.004

[5] Liu, C.Q. and Wen, L.H. (2022) Development Status and Analysis of Missile Family Architecture for Terminal Air Defense Missiles. *Modern Defense Technology*, **50**, 45-51.

[6] Zhang, J., Yu, B.S. and Zheng, S.J. (1996) Research on the Overall Technology of the Family of Air Defense Missiles. *Systems Engineering and Electronic Technology*, **5**, 3-13.

[7] Xiao, Y. and Wu, Z.C. (2013) Modular Simulation of Missiles Based on Matlab/Simulink. *Journal of Terahertz Science and Electronic Information*, **11**, 399-401+410.