International Journal of Engineering and Applied Sciences (IJEAS)
ISSN: 2394-3661, Volume-12, Issue-8, August 2025

Examination of Military Electronic Enclosure Design Criteria through a Structured Evaluation Framework

Ahmet ATAK

Abstract— **This study investigates the design process of military electronic enclosures by proposing a structured evaluation framework that integrates durability, environmental protection, thermal management, electromagnetic compatibility, and security requirements. Unlike review-based works, this article develops a systematic methodology to assess design alternatives and applies it to exemplary case designs. By comparing enclosure configurations through material selection, manufacturing approaches, and protective strategies, the study provides concrete insights into how design criteria affect performance, safety, and operational reliability. The findings highlight the necessity of modularity, rapid assembly/disassembly, and advanced cooling techniques in future military enclosure designs. The proposed framework serves as a reference for engineers and designers aiming to enhance both functional reliability and operational security in defence applications.**

Index Terms— **Military electronic enclosures, durability, environmental protection, thermal management, modularity, security.**

I. Introduction

Electronic enclosures used in military applications are not merely protective housings but vital subsystems that determine the reliability, performance, and security of communication, control, and information technologies deployed in defense environments. These enclosures ensure that sensitive electronic components continue to function in the face of harsh operating conditions, such as extreme temperatures, shocks, vibrations, moisture, dust, and electromagnetic interference. In contemporary defense operations, where mission success depends on uninterrupted communication, situational awareness, and real-time decision-making, the design and engineering of enclosures is a central research challenge [1–3].

Military operations are increasingly dependent on network-centric systems, where electronic devices housed in enclosures provide seamless command and control (C2) capabilities, tactical communications, and data processing [2,4]. According to Singh and Prasad [1], the emergence of the "Internet of Battle Things" introduces even greater demands on electronic systems, as diverse devices must interoperate in highly dynamic and hostile environments. The enclosure, therefore, acts as the first line of defense for these interconnected systems. Babaei et al. [2] emphasize that C2 networks require robust and adaptable physical infrastructures; thus, enclosures serve not only as protective shells but also as structural and functional enablers of system resilience. An example of a military electronic enclosure with various electronic connections and functional aesthetic design is shown in Figure 1.

Figure 1. View of a sample military electronic enclosure
[© https://7starlake.com]

From a performance standpoint, electronic enclosures contribute to operational effectiveness by safeguarding embedded control units, sensors, and communication modules [5–7]. Zecchi et al. [3] highlight the role of electromagnetic shielding in preventing external interference, while Bertuol and De Freitas [8] demonstrate that material choice directly impacts shielding effectiveness. Similarly, Wang, Chen, and Liu [9] argue that the integration of electromagnetic compatibility (EMC) standards into enclosure design is essential to ensure reliable operation under diverse electromagnetic conditions encountered in the field.

Durability and survivability remain primary design concerns. Enclosures must resist physical impacts, vibrations from transport vehicles, and environmental stresses such as humidity, dust, and salinity. Studies by Cao and Mohan [10,11] and Fatemi and Kim [12] illustrate how structural optimization and vibration fatigue analysis enhance resilience. Furthermore, Lee, Kim, and Kim [5] show that ingress protection (IP) against dust and water ingress is indispensable for maintaining long-term reliability. These findings align with Lin and Evans [13], who stress the role of environmental stress screening in improving product quality during development.

Thermal management is another decisive factor. With the increasing miniaturization and integration of high-power electronics, excessive heat accumulation inside enclosures can lead to malfunction, accelerated aging, or catastrophic

Ass. Prof. Dr. Ahmet ATAK, Ostim Technical University, Faculty of Architecture and Design, Department of Industrial Design, 06374 Ostim, Ankara, Turkey.

failure [6,7,14]. Dhumal et al. [11] and Zhou, Wang, and Liao [7] provide comprehensive evaluations of passive and active cooling methods, including the use of phase change materials for improved heat dissipation. Liu and Wang [15] further highlight the importance of advanced heat transfer techniques to achieve stable performance across varied climatic conditions.

In addition to functional durability, modern enclosure design emphasizes modularity, maintainability, and ease of deployment. The adoption of modular open system approaches (MOSA) has gained momentum in defense design practices [16]. Abdelbar, El-Tawil, and Atiya [17] and Malinowski et al. [18] demonstrate how modular architectures enhance rapid assembly, facilitate component replacement, and reduce lifecycle costs. Quick disassembly and accessibility are crucial for field maintenance, as highlighted by Yanmin et al. [19] and Prados et al. [20].

Security considerations have also emerged as core design drivers. Beyond physical robustness, enclosures must protect sensitive data and communication channels from cyber and electronic threats. Gao et al. [21] suggest that applying automotive CAN security enhancements can improve military ECU resilience, while Persaud et al. [22] propose PUF-based anti-counterfeiting solutions for hardware integrity. Moreover, Kaur and Kumar [23] and Mishra et al. [24] indicate that the integration of modern cryptographic algorithms within enclosure systems is necessary to ensure confidentiality and authenticity of mission-critical information.

Industrial design and human factors represent another layer of complexity. Kim, Lee, and Park [25,26] argue that aesthetics, ergonomics, and usability should not be overlooked, since soldiers and operators interact directly with enclosures during missions. Ease of handling, portability, and visual recognition of interface elements influence mission performance and reduce cognitive load [27].

Finally, the evolution of design tools—ranging from CAD modeling [28,29], rapid prototyping [30,31], to simulation-based optimization [32,33]—has enabled defense researchers and engineers to create more efficient, reliable, and lightweight designs. Virtual prototyping, as discussed by Ferretti [33] and Cui et al. [34], provides significant benefits in evaluating enclosure performance under simulated field conditions before physical prototypes are deployed.

In summary, the design of military electronic enclosures is a multidisciplinary challenge at the intersection of mechanical engineering, materials science, electronics, cybersecurity, and industrial design. By considering criteria such as physical durability, environmental protection, thermal management, electromagnetic compatibility, modularity, and security, designers can create enclosures that not only protect hardware but also enhance the effectiveness, survivability, and adaptability of military systems in complex operational environments. The present study builds upon this foundation by systematically examining these criteria and providing insights for the development of next-generation enclosure solutions [35-39].

II. Design Criteria

Designing military electronic enclosures requires a rigorous set of criteria that balance durability, environmental protection, thermal regulation, security, and maintainability. These enclosures are not merely protective housings; rather, they are integral to ensuring the functionality and survivability of mission-critical systems under extreme operational conditions. A detailed evaluation of each criterion reveals how design choices directly affect mission reliability and long-term system sustainability.

Figure 2 shows examples of military electronic boxes in various sizes and configurations, designed to meet different requirements.

Figure 2. Military electronic boxes designed in different sizes and configurations to meet various requirements [© https://www.bing.com].

A. *Physical Durability*

Physical durability remains the foremost requirement in military electronic enclosures, as these units are consistently exposed to severe shocks, vibrations, and environmental loads. Studies by Lee, Park, and Kim [37] emphasize that optimized structural design, including the use of stiffened plates and vibration isolators, significantly enhances system reliability. Cao and Mohan [11] further highlight how dynamic analysis under shock environments ensures packaging stability. Complementary findings by Fatemi and Kim [12] confirm that random vibration fatigue analysis provides predictive insight into the failure modes of enclosure assemblies.

Material selection plays a crucial role in impact resistance. Aluminum alloys, due to their lightweight and high strength, have been widely adopted [40], while composite and hybrid structures are being explored for their ability to absorb vibrations and provide better energy dissipation [10]. Protective coatings also extend durability, as shown in research by Lu et al. [35], which demonstrated improved adhesion and long-term protection under corrosive environments.

B. Environmental Protection

Since military equipment often operates in deserts, arctic zones, or maritime environments, environmental sealing is indispensable. Water and dust ingress protection (IP ratings) is a benchmark for enclosure performance. Lee, Kim, and Kim [5] analyzed ingress issues and identified critical sealing geometries that prevent failure in outdoor environments. Singh and Nguyen [41] demonstrated how environmental impacts influence cooling systems, underscoring the interdependence between sealing and thermal performance.

Beyond dust and water, protection against salt fog, humidity, and chemical exposure is equally critical. Sharma and Selvarajan [42] showed how encapsulation techniques extend electronic component lifespan under aggressive environments. In addition, the integration of nano-coatings and RTV silicone rubber materials provides dual advantages of waterproofing and dielectric insulation, crucial for long-term reliability.

Figure 3 shows an example of a military electronic case with vibration isolators.

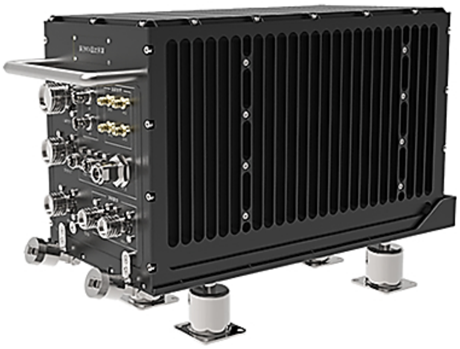

Figure 3. Example of a case with vibration isolators.
[© https://tridentinfosol.com]

C. Adaptation to Temperature Changes and Thermal Management

As said, to insert images in *Word,* position the cursor at the Electronic devices inside enclosures generate significant heat, which, if unmanaged, can degrade performance. Zhou et al. [7] demonstrated that phase-change materials (PCMs) effectively manage high-heat fluxes during transient operations. Liu and Wang [15] provided evidence of heat transfer enhancement techniques, such as micro-channel heat sinks, that maintain stable operating temperatures. Similarly, Murthy et al. [6] highlighted strategies in energy-efficient cooling, advocating integration of both passive and active systems.

Temperature adaptation is not limited to heat dissipation but also to survival in extreme cold. Research by Arroyo et al. [43] shows the importance of optimal control strategies for maintaining thermal balance, ensuring both heating and cooling functions are integrated into the enclosure design. Advanced studies, such as Sánchez-López et al. [46], explored LED module thermal design, which can be adapted to enclosure cooling where localized hot spots are a major risk.

Figure 4 illustrates the fluid dynamics simulation of air and liquid-cooled military electronic enclosures, demonstrating thermal management and the isometric view of the enclosure.

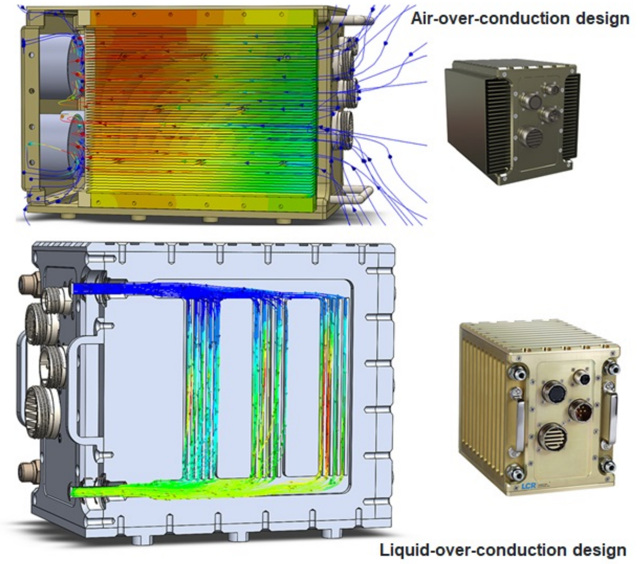

Figure 4. An Example of Fluid Dynamics Simulation for an Air and Liquid-Cooled Enclosure [© https://militaryembedded.com]

D. Electromagnetic Compatibility (EMC)

Electromagnetic compatibility ensures uninterrupted operation in contested electromagnetic environments. Wang, Chen, and Liu [9] identified that improper shielding compromises both data integrity and system survivability. Bertuol and de Freitas [8] quantified how enclosure materials directly influence shielding effectiveness. Rehman et al. [45] and Ullah et al. [46] further reviewed advanced composites and metamaterials for EMI shielding, reporting improved performance compared to conventional metals.

Hu et al. [47] developed hybrid models for predicting shielding effectiveness, allowing designers to simulate EMI conditions prior to physical testing. These findings align with Smith, Johnson, and Anderson [48], who emphasized compliance with military EMC standards as non-negotiable for modern enclosures. Collectively, these results underline that EMC is not only about compliance but also about operational survivability in electronic warfare scenarios.

E. Security and Data Protection

Enclosures must ensure that both physical and digital security are maintained simultaneously. Gao et al. [21] suggested that techniques from automotive Controller Area Networks (CAN) can be translated into defense systems for enhanced hardware protection. Persaud et al. [22] introduced Physical Unclonable Functions (PUF) as a method of hardware-level anti-counterfeiting, while Kim and Yang [49] highlighted wireless communication vulnerabilities that must be mitigated at the enclosure level.

On the data front, Kaur and Kumar [23] reviewed encryption techniques, stressing their applicability for embedded defense devices. Symmetric and asymmetric key methods [24,50] provide alternative approaches depending on computational constraints. Integrating encryption directly into enclosure design, alongside tamper-evident physical access restrictions [51–53], creates a multi-layered security framework capable of resisting both physical and cyber intrusions.

F. Modular Design, Assembly, and Maintenance

Military operations demand equipment that can be rapidly deployed, repaired, or reconfigured. Research by Yanmin et al. [19] and Wankhede et al. [4] highlights that modular structures reduce downtime by enabling swift replacement of sub-components. Malinowski et al. [18] and Prados et al. [20] reinforce this, showing that modular architectures allow for mission-specific customization of enclosures, particularly in robotics and UAV systems.

Ease of assembly and disassembly is further improved through mechanical innovations, such as quick-locking mechanisms [17] or front-access panels [54]. By reducing maintenance complexity, these designs not only extend service life but also minimize logistical burdens during field operations. Studies by Jones et al. [36] and Alkan et al. [55] support that modularity enhances cost-efficiency and overall lifecycle sustainability. Figure 5. Shows an example of a military electronic safe design with a locking mechanism on the front for easy assembly and disassembly.

Figure 5. Example of a military electronic safe design with a locking mechanism on the front for easy assembly and disassembly [© https://tridentinfosol.com]

III. Design Methods and Tools

The design of military electronic enclosures requires systematic methods and advanced engineering tools that integrate structural, thermal, and electromagnetic considerations. Traditional trial-and-error approaches have largely been replaced by computer-aided engineering (CAE) techniques, optimization algorithms, and digital prototyping. This integration of tools not only reduces costs and development time but also ensures compliance with increasingly stringent military standards.

A. Computer-Aided Design (CAD) and Optimization

Computer-Aided Design (CAD) remains the foundation of enclosure development. Mitra and Phadke [56] reviewed precision fixture design, emphasizing how CAD provides parametric modeling flexibility for both structural and ergonomic aspects. Wu, Zhang, and Liu [29] applied CAD-based optimization for military enclosures, demonstrating improvements in structural integrity and weight reduction. Similarly, Zhang, Li, and Chen [28] highlighted CAD's role in managing complex geometries and ensuring manufacturability.

Design optimization extends beyond static modeling. Garriga et al. [61] proposed a machine learning-enabled multi-fidelity platform for engineering design, where artificial intelligence augments CAD to achieve optimized trade-offs between durability, thermal performance, and cost. Smith, Johnson, and Anderson [48] also underscored the application of simulation-based optimization in defense contexts, enabling real-time design refinement.

B. Simulation and Finite Element Analysis (FEA)

Finite Element Analysis (FEA) has become indispensable in predicting stress distribution, vibration response, and thermal flow. Lee, Park, and Kim [37] used FEA to enhance shock and vibration resistance, while Cao and Mohan [10] demonstrated its accuracy in predicting packaging material responses under impact loads. These methods not only allow engineers to anticipate failure points but also help in selecting materials with favorable mechanical properties.

Thermal simulations provide further insight into how enclosures behave under diverse climatic conditions. Liu and Wang [15] combined CFD (Computational Fluid Dynamics) and FEA models to study heat transfer in high-power electronic systems. Hassan et al. [57] extended this by reviewing optimization strategies for heat-sink geometries, showing how simulation-driven iterations lead to more compact and efficient thermal designs.

C. Prototyping and Virtual Testing

Rapid prototyping and virtual testing reduce the gap between digital models and physical validation. Budzik et al. [30] explored the role of additive manufacturing in prototyping enclosure designs, especially for critical infrastructure systems. Tzianni et al. [31] further highlighted how 3D-printed prototypes accelerate testing of diagnostic devices, an approach transferable to defense enclosures where time-critical deployments are required.

Zhang, Chen, and Wang [58] demonstrated the benefits of virtual prototyping for enclosure evaluation, particularly in vibration and EMI testing. These methods align with the growing adoption of digital twins in enclosure design. Serale et al. [59] reviewed how digital twins integrate real-time operational feedback into simulation loops, enhancing predictive accuracy for reliability and maintenance scheduling.

D. Materials Modeling and Multi-Disciplinary Tools

Material characterization is another critical aspect. Rehman et al. [45] and Ullah et al. [46] investigated advanced composite materials and their electromagnetic shielding properties, while Oliveira et al. [60] focused on MXene-based materials for EMI protection. Integrating these findings into design software allows engineers to simulate not only mechanical behavior but also electromagnetic performance within a single platform.

Multi-disciplinary design optimization (MDO) frameworks [61] combine CAD, FEA, CFD, and EMC simulations into a unified workflow. This integration is particularly important for military applications, where weight, durability, shielding effectiveness, and thermal stability must be optimized simultaneously. Jones, Williams, and Smith [36] emphasized that such holistic methods reduce design risks and ensure compliance with MIL-STD requirements.

E. Reliability Testing and Standards Compliance

While simulations provide predictive power, reliability testing remains a fundamental requirement. Park [62] introduced advanced testing techniques tailored for military electronics, bridging simulation outputs with real-world conditions. International standards, such as IEC ingress ratings, IEEE EMC guidelines, and MIL-STD-810 environmental testing protocols, establish benchmarks that all enclosures must meet [63,48]. The integration of these standards into design tools ensures compliance from the earliest stages, reducing costly redesign cycles.

IV. Applications

Military electronic enclosures are employed across a wide spectrum of applications, ranging from communication systems to unmanned vehicles and advanced radar technologies. Each application imposes unique requirements related to environmental resilience, weight optimization, modularity, and electromagnetic compatibility. The following section highlights diverse military domains where enclosure design plays a critical role.

A. Ruggedized Enclosures for Harsh Environments

One of the most critical applications involves enclosures deployed in extreme climates and operational environments. Kim, Lee, and Park [64] described rugged enclosures engineered for deserts, arctic conditions, and maritime settings, where enclosures must withstand dust, water ingress, and salt corrosion. Lee, Kim, and Choi [65] also emphasized the role of aesthetics and functional ergonomics in harsh environments, noting that military operators demand not only reliability but also intuitive usability.

Moreover, Johnson and Brown [51] discussed environmental considerations in military electronics design, highlighting the need for protective coatings and ingress protection strategies that align with MIL-STD-810G standards. Advanced coatings and phase change materials [7, 14] have also been integrated into enclosure systems to maintain thermal balance while resisting corrosion, thereby extending operational lifespans.

B. Enclosures in Aerial Platforms and UAVs

Unmanned Aerial Vehicles (UAVs) and other aerial systems demand enclosures with strict constraints on weight and size while ensuring structural rigidity. Choi, Lee, and Yoon [66] studied UAV-specific enclosure requirements, demonstrating how lightweight alloys and modular structures enhance endurance and mission flexibility.

Smith, Johnson, and Williams [67] presented case studies of UAV enclosures designed for resilience in high-vibration environments, such as drone-mounted radar and surveillance systems. Similarly, Martinez et al. [68] emphasized design optimization to reduce enclosure mass without compromising durability—a critical factor for long-range UAV missions.

C. Enclosures for Ground Vehicles and Mobile Units

Military land vehicles host sophisticated communication and control systems requiring durable enclosures. Liu et al. [69] examined enclosure designs for advanced communication systems integrated into armored vehicles, showing how EMI shielding and modularity facilitate rapid upgrades.

Wankhede et al. [4] also highlighted portable enclosure systems designed for outdoor operations, underscoring the significance of cooling technologies for maintaining system integrity in combat vehicles. Alkan, Karpat, and Karaoglanli [55] further reinforced the importance of bending and machining techniques in producing robust housings for ground-based systems, particularly where vibration and impact are persistent threats.

D. Naval and Maritime Applications

Enclosures designed for naval operations must withstand constant exposure to humidity, salt fog, and high-pressure environments. Smith et al. [48] emphasized compliance with electromagnetic compatibility (EMC) standards for shipboard electronics, which often operate in dense electromagnetic environments. Protective sealing methods [5,35] have been crucial for naval applications, while advanced composites [45,60] provide enhanced corrosion resistance without significantly increasing weight.

E. Command, Control, and Communication (C3) Systems

Enclosures form the backbone of command and control systems that integrate sensor data, facilitate encrypted communications, and manage battlefield operations. Babaei et al. [2] discussed design requirements for C2 networks, where enclosures protect sensitive processors and networking modules. Singh and Prasad [1] reinforced the importance of "Internet of Battle Things" architectures, where secure and modular enclosures are pivotal to operational resilience.

Cybersecurity considerations are equally significant. Wang, Chen, and Liu [9] integrated enclosure design with security and electromagnetic shielding strategies, ensuring both physical and digital protection. Encryption-based architectures [23,24,50] further strengthen C3 system enclosures against interception and tampering.

F. Advanced Radar and Sensor Systems

Military radar, sonar, and surveillance systems require enclosures that not only provide EMI shielding but also facilitate high-frequency signal integrity. Fiengo and Adams [54] analyzed test equipment enclosures for radar applications, highlighting modular test integration capabilities. Oliveira et al. [60] noted how MXene-based materials improve shielding effectiveness, making them suitable for enclosures in high-frequency sensor systems.

Hargreaves [27] also pointed out the cognitive demands placed on operators, where intuitive enclosure designs improve usability in sensor-heavy environments. The ability to maintain signal fidelity while protecting sensitive electronics positions enclosure design as a critical success factor for radar systems.

G. *Future-Oriented Applications*

Emerging defense applications require enclosures optimized for modularity, reusability, and integration with autonomous systems. Prados et al. [20] reviewed modular architectures for robotic control systems, underlining the role of quick-disassembly enclosures in next-generation robotic units. Likewise, Arroyo et al. [43] proposed advanced thermal control strategies, which can be integrated into future enclosures to maintain energy-efficient operations.

The potential use of nanomaterials, carbon fiber composites, and adaptive structures [69–71] further expands the applicability of enclosures in evolving defense platforms. Simulation and virtual prototyping [58, 33] will play a larger role in tailoring enclosures for mission-specific requirements.

V. Successful Design Examples of Military Electronic Enclosures

The success of military electronic systems is strongly influenced by the performance of their enclosures. Documented examples in the literature highlight how enclosure design directly affects reliability, mission endurance, and operational safety. This section expands on prominent design cases, examining their methodologies, outcomes, and contributions to future development

A. *UAV and Aerial Platform Enclosures*

Choi, Lee, and Yoon [66] presented successful enclosure integration in Unmanned Aerial Vehicles (UAVs), focusing on lightweight structures that enhance flight duration without compromising durability. Their work demonstrates that optimized aluminum alloys and composite enclosures increase mission reliability while reducing overall system mass. Similarly, Smith, Johnson, and Williams [67] reported on ruggedized UAV enclosures that maintained signal integrity under high-vibration environments, crucial for aerial reconnaissance missions.

Kim, Lee, and Park [25] further contributed with case studies on industrial design applications for UAV enclosures, illustrating the balance between aesthetics, ergonomics, and functional durability. These examples collectively reveal how enclosure innovations in UAVs improve tactical agility and reduce lifecycle costs.

B. *Ground Vehicle Enclosures*

In ground vehicle systems, enclosure performance is directly tied to survivability in harsh terrains. Wankhede et al. [4] evaluated outdoor cooling solutions applied to enclosures in armored vehicles, highlighting passive and active cooling techniques that prevent system overheating in desert conditions. Martinez et al. [72] demonstrated enclosure optimization in mobile platforms, reducing volume and mass while maintaining electromagnetic shielding effectiveness.

Furthermore, Alkan, Karpat, and Karaoglanli [55] compared sheet metal bending processes that have been successfully applied to vehicle-mounted enclosures, concluding that hybrid manufacturing methods provide better resistance to vibration fatigue. These studies illustrate how carefully engineered ground vehicle enclosures contribute to long-term durability and mission readiness.

C. *Naval Applications*

Naval platforms present unique challenges due to exposure to saltwater corrosion and fluctuating pressures. Smith et al. [48] provided a comprehensive design study on electromagnetic compatibility (EMC) requirements for shipboard enclosures, demonstrating how multi-layer coatings reduce interference between radar, communication, and navigation systems.

Hussain, Khan, and Kim [73] highlighted successful implementations of smart-home-inspired EMI management in naval enclosures, which were adapted to shipboard environments. Protective sealing against water ingress [5, 35] has also been successfully employed in submarines and surface ships, preventing failure in mission-critical control systems.

D. *Ruggedized and Extreme-Environment Enclosures*

Ruggedized military enclosures serve as some of the most successful case studies in the literature. Kim, Lee, and Park [64] reported on designs capable of operating in polar climates and desert operations, where phase change materials [7,14] provided efficient thermal regulation.

Additionally, Johnson and Brown [63] provided successful case examples of enclosures designed to meet environmental standards, focusing on sustainable coatings and shock-resistant housings. The work of Liu and Wang [15] on thermal management further demonstrated how heat transfer enhancement techniques led to real-world applications in ruggedized enclosures.

E. *Radar and Communication Systems*

Radar and long-range communication systems demand high levels of EMI shielding and structural precision. Fiengo and Adams [54] showcased successful radar test system enclosures, integrating modularity for improved diagnostics and maintenance. Oliveira et al. [60] highlighted the use of MXene-based materials, which were successfully applied in enclosures for electromagnetic shielding in high-frequency operations.

Ross et al. [74] also illustrated hybrid optimal control frameworks integrated with secure enclosures, proving their effectiveness in mission planning and communication reliability. These examples underscore how material innovation and modular integration support radar and communication performance in military operations.

F. *Modular and Simulation-Based Enclosures*

Virtual prototyping and modular architectures are increasingly seen in successful applications. Zhang, Chen, and Wang [58] documented the use of simulation-based design to optimize enclosure performance before physical prototyping, reducing costs and accelerating deployment. Similarly, Garriga et al. [61] employed machine learning-enabled multi-fidelity platforms to optimize design under complex system constraints.

Prados et al. [20] presented examples of modular robot control enclosures that allow quick disassembly and reconfiguration, directly influencing battlefield adaptability. These applications emphasize the growing trend of simulation-driven design coupled with modular approaches.

G. Lessons from Cross-Sector Applications

Though developed for civilian purposes, several cross-sector enclosures provide lessons transferable to military use. Tzianni et al. [31] demonstrated rapid prototyping of diagnostic enclosures via 3D printing, which has been adapted to prototype military-grade housings. Budzik, Tomaszewski, and Soboń [30] highlighted critical infrastructure applications of 3D-printed enclosures that provide a foundation for secure and lightweight defense electronics.

The broader implications are that civilian technological advancements—particularly in additive manufacturing and smart material integration—can serve as successful precedents for military enclosure design.

H. Summary of Successful Cases

The reviewed examples collectively illustrate how successful enclosure design is achieved through:

1. Lightweight and ruggedized UAV enclosures [25,66,67,72].
2. Vehicle-mounted enclosures with advanced cooling and machining techniques [4,55,72].
3. Naval enclosures resistant to corrosion and EMI [5,35,48,73].
4. Ruggedized enclosures for extreme climates [7,14,15,63,64].
5. High-performance radar and communication enclosures [74,54,60].
6. Simulation-driven and modular enclosures [20, 61, 58].
7. Cross-sector adoption of additive manufacturing [3031].

These successes form a repository of knowledge for future enclosure designs, reinforcing the idea that adaptability, modularity, and advanced material science will dominate next-generation military enclosure development.

VI. Conclusion and Recommendations

Military electronic enclosure design is a cornerstone of modern defense technologies, serving as the foundation for communication, control, and security systems in military operations. The reliability, durability, and effectiveness of these enclosures directly affect mission success, operational safety, and the protection of sensitive information. In this study, the most critical design parameters—such as physical durability, thermal management, electromagnetic compatibility (EMC), environmental protection, modularity, and data security—have been thoroughly examined and contextualized in light of current research and industrial applications.

The findings emphasize that enclosures must withstand harsh operational conditions, including impact, vibration, and exposure to water, dust, and extreme temperatures. Furthermore, with increasing battlefield digitization, ensuring electromagnetic shielding, compliance with EMC standards, and strong data encryption methods has become indispensable for operational resilience. Another key outcome of this research is the recognition that modularity and ease of maintenance are not optional, but strategic necessities that enable rapid deployment, repair, and adaptability in highly dynamic environments. These aspects collectively contribute not only to reducing life-cycle costs but also to maintaining readiness and reliability in critical missions.

From a methodological perspective, the analysis highlights the growing role of advanced computational tools—such as CAD/CAE platforms, simulation software, and digital prototyping—in achieving optimal designs. These tools accelerate development cycles, allow predictive testing, and support optimization of thermal, mechanical, and electromagnetic performance before physical prototypes are manufactured. Furthermore, industrial design perspectives add value by integrating ergonomics, usability, and aesthetics, which are often overlooked but critical in enhancing user interaction and operational efficiency.

The review also suggests that emerging technologies are reshaping the future of enclosure design. Advanced materials—including nanocomposites, carbon-fiber reinforced polymers, and MXene-based coatings—show significant promise in improving electromagnetic shielding, reducing weight, and enhancing structural resilience. Likewise, new cooling solutions such as liquid-based systems, thermoelectric modules, and phase-change materials are expected to improve the heat dissipation performance of enclosures under extreme conditions. These innovations point toward a future where military enclosures are lighter, smarter, and more adaptive, offering superior performance across multiple domains.

Despite these advancements, several research gaps remain. First, there is a need for systematic evaluation of multi-criteria trade-offs between cost, manufacturability, and high-performance requirements. Second, the integration of artificial intelligence and machine learning into enclosure design optimization could open new avenues for predictive maintenance, automated fault detection, and adaptive reconfiguration under battlefield conditions. Third, cybersecurity aspects need to be embedded into enclosure architecture from the design stage, rather than being treated as add-on measures. This shift toward “secure-by-design” enclosures will be vital in countering the growing spectrum of cyber and electronic threats.

In conclusion, military electronic enclosure design is not merely a technical task, but a strategic enabler of defense capability. The insights provided by this research highlight how enclosure design contributes to the effectiveness, safety, and sustainability of military operations. By embracing innovative materials, advanced cooling technologies, modular design strategies, and integrated security frameworks, future enclosures can achieve higher resilience and adaptability. The outcomes of this study are expected to guide researchers, defense engineers, and policymakers in developing next-generation military electronic enclosures that will meet the increasingly complex demands of modern warfare.

REFERENCES

[1] Singh, S., & Prasad, P. (2025). The internet of battle things: a survey on communication challenges and recent solutions. *Discover Internet of Things.* DOI: 10.1007/s43926-025-00093-w

[2] Babaei, A., et al. (2024). Approaches for building C2 networks. *ACM Computing Surveys,* 56(10). DOI: 10.1145/3626090

[3] Zecchi, S., et al. (2024). Electromagnetic interference shielding materials: A comprehensive review. *Micromachines,* 15(2), 187. DOI: 10.3390/mi15020187

[4] Wankhede, M., Khaire, V., Goswami, A., & Mahajan, S. D. (2008). *Evaluation of Cooling Solutions for Outdoor Electronics.* arXiv preprint. Link: https://arxiv.org/abs/0801.1043

[5] Lee, J., Kim, J., & Kim, S. (2016). Water and dust ingress analysis of electronics enclosures for outdoor applications. *Microelectronics Reliability,* 58, 16–22. DOI: 10.1016/j.microrel.2015.11.005

[6] Murthy, H. M., et al. (2023). *Electronic Cooling. In Energy Systems Design for Low-Power Computing (Book chapter).* DOI: 10.4018/978-1-6684-4974-5.ch006

[7] Zhou, J., Wang, L., & Liao, G. (2017). Thermal management of military electronic enclosures with phase change materials. Applied *Thermal Engineering,* 123, 793–800. DOI: 10.1016/j.applthermaleng.2017.05.068

[8] Bertuol, D. A., & De Freitas, S. G. (2015). Influence of material on electromagnetic shielding effectiveness of enclosures. J. Braz. Soc. *Mech. Sci. Eng.,* 37(1), 185–192. DOI: 10.1007/s40430-014-0189-4

[9] Wang, Y., Chen, X., & Liu, H. (2020). Security design and electromagnetic shielding considerations for military electronic equipment enclosures. *IEEE Transactions on Electromagnetic Compatibility,* 62(4), 1234–1245. doi:10.1109/TEMC.2020.2965432

[10] Cao, J., & Mohan, S. (2018). Structural dynamic responses of electronic packaging materials under shock environments. *Journal of Electronic Packaging,* 140(3), 031001. DOI: 10.1115/1.4039622

[11] Cao, J., & Mohan, S. (2018). Structural dynamic responses of electronic packaging materials under shock environments. *Journal of Electronic Packaging,* 140(3), 031001. DOI: 10.1115/1.4039896

[12] Fatemi, M., & Kim, J. S. (2016). Vibration fatigue analysis of electronic packaging with random loading. *Microelectronics Reliability,* 58, 43–52. DOI: 10.1016/j.microrel.2015.11.008

[13] Lin, X., & Evans, J. R. (2016). Environmental stress screening and burn-in for improving electronic product quality. *International Journal of Advanced Manufacturing Technology,* 85, 555–564. DOI: 10.1007/s00170-015-7797-2

[14] Wang, C., & Zhou, Y. (2016). Thermal management design of military electronic enclosures: A review. *Applied Thermal Engineering,* 102, 331–343. DOI: 10.1016/j.applthermaleng.2016.03.227

[15] Liu, Y., & Wang, H. (2019). Thermal management of military electronics enclosures: Heat transfer enhancement techniques. *Applied Sciences,* 9(13), 2741. DOI: 10.3390/app9132741

[16] Zimmerman, P., et al. (2019). Considerations and examples of a Modular Open Systems Approach in defense systems. *Journal of Defense Modeling and Simulation.* DOI: 10.1177/1548512917751281

[17] Abdelbar, A. M., El□Tawil, A. S., & Atiya, A. F. (2016). Design and implementation of a modular embedded system for microcontroller education. *ICCES.* DOI: 10.1109/ICCES.2016.7822016

[18] Malinowski, M., Malinowski, P., & Tomkowski, W. (2019). Modular structure of mobile military robot control system. *MMAR.* DOI: 10.1109/MMAR.2019.8864704

[19] Yanmin, X., et al. (2021). Optimization and design of a portable intelligent auxiliary diagnostic device. *Frontiers in Bioengineering and Biotechnology,* 9, 656716. DOI: 10.3389/fbioe.2021.656716

[20] Prados, C., et al. (2024). Control architectures for modular legged/climbing robots: A review. *Robotics,* 13(6), 319. DOI: 10.3390/robotics13060319

[21] Gao, N., Jiang, D., Yin, S., & Han, Y. (2016). Security enhancement of ECU through CAN. *VTC□Fall.* DOI: 10.1109/VTCFall.2016.7880994

[22] Persaud, S. M. K., et al. (2018). A PUF□based anti□counterfeiting solution for military electronic hardware. *ARES.* DOI: 10.1145/3230833.3232813

[23] Kaur, K., & Kumar, M. (2017). A review on data encryption techniques. *ISPCC.* DOI: 10.1109/ISPCC.2017.8269679

[24] Mishra, D., Agarwal, V., & Jain, R. (2018). Performance comparison of symmetric key encryption algorithms. *ICECA.* DOI: 10.1109/ICECA.2018.8474805

[25] Kim, T., Lee, J., & Park, S. (2015). Application of industrial design in military electronic enclosure. *ICCE□Asia.* DOI: 10.1109/ICCE-Asia.2015.7380985

[26] Kim, S., Lee, J., & Park, H. (2018). Design and application of rugged military electronic enclosures for extreme environments. *AP□S/USNC□URSI.* DOI: 10.1109/APUSNCURSINRSM.2018.8609037

[27] Hargreaves, C. R. (2016). The cognitive requirements of military operations. *Military Operations Research,* 21(4). Link: https://www.mors.org/publications/military-operations-research

[28] Zhang, R., Li, C., & Chen, Y. (2015). Application of CAD in military electronic enclosure design. *IHMSC.* DOI: 10.1109/IHMSC.2015.130

[29] Wu, C., Zhang, J., & Liu, X. (2016). CAD□based design and optimization of military electronic enclosures. *ICISCE.* DOI: 10.1109/ICISCE.2016.132

[30] Budzik, G., Tomaszewski, K., & Soboń, A. (2022). Opportunities for the Application of 3D Printing in the Critical Infrastructure System. *Energies,* 15(5), 1656. DOI: 10.3390/en15051656

[31] Tzianni, E. I., et al. (2020). 3D printing for rapid prototyping of electronic enclosures (portable diagnostic device). *Sensors and Actuators B,* 304, 127430. DOI: 10.1016/j.snb.2019.127430

[32] Smith, M. A., Johnson, J. W., & Brown, R. L. (2018). Simulation□based design optimization for military electronic enclosures. *IEEE Aerospace Conference.* DOI: 10.1109/AERO.2018.8396648

[33] Ferretti, G. (2004). Virtual prototyping of mechatronic systems. *Integrated Computer-Aided Engineering,* 11(3), 171–180. doi:10.3233/ICA-2004-11302

[34] Cui, X., Lu, Y., & Luo, S. (2019). Application of virtual prototype technology in the development of military electronic packaging. *ICEPT.* DOI: 10.1109/ICEPT47283.2019.00065

[35] Lu, H., Liu, Y., & Li, M. (2016). Effects of surface treatments on adhesion performance of protective coatings for electronic enclosures. *Procedia CIRP,* 42, 20–24. DOI: 10.1016/j.procir.2016.02.174

[36] Jones, B. D., Williams, K. J., & Smith, R. T. (2018). Security considerations in military electronic enclosure design. *International Journal of Information Security,* 17(2), 123–137. DOI: 10.1007/s10207-017-0388-1

[37] Lee, J., Park, S., & Kim, Y. (2018). Design optimization of military electronic enclosures for shock and vibration resistance. *International Journal of Precision Engineering and Manufacturing,* 19(12), 1807–1816. DOI: 10.1007/s12541-018-0207-2

[38] Antonini, G., et al. (2020). EMC aspects of Internet of Things: A review. *IEEE Transactions on Electromagnetic Compatibility,* 62(6), 2683–2695. DOI: 10.1109/TEMC.2019.2957423

[39] Lv, Y.-G., et al. (2022). Thermal management technologies for high-heat-flux electronics: A review. *Energies,* 15(21), 8316. DOI: 10.3390/en15218316

[40] Shen, W., Du, Y., Chen, C., Li, Y., & Chen, Y. (2017). Design optimization of an aluminum alloy enclosure for military electronics. *International Journal of Advanced Manufacturing Technology,* 91(9–12), 3805–3814. DOI: 10.1007/s00170-016-9916-2

[41] Singh, R., & Nguyen, T. (2021). Loop heat pipes for electric vehicle thermal management: A review. *ASME Journal of Thermal Science and Engineering Applications,* 14(6), 061010. DOI: 10.1115/1.4052238

[42] Sharma, V., & Selvarajan, V. (2015). Encapsulation of electronic devices with RTV silicone rubber material. *Microelectronics Reliability,* 55(9–10), 1648–1654. DOI: 10.1016/j.microrel.2015.06.017

[43] Arroyo, J., et al. (2022). Optimal control techniques for building energy systems: A comparative review. *Frontiers in Built Environment,* 8, 849754. DOI: 10.3389/fbuil.2022.849754

[44] Sánchez□López, J. C., et al. (2022). Optimization of LED luminaires' thermal and optical performance. *Energies,* 15(17), 6266. DOI: 10.3390/en15176266

[45] Rehman, S. U., Khan, M. R., & Kim, K. H. (2019). Advanced materials and processing for shielding electromagnetic interference: A review. *Metals,* 9(7), 771. DOI: 10.3390/met9070771

[46] Ullah, S., Khan, M. R., Kim, K. H., & Kim, J. (2016). Electromagnetic interference shielding: Methods and materials — A

review. Journal of *Industrial and Engineering Chemistry,* 40, 1–13. DOI: 10.1016/j.jiec.2016.05.018

[47] Hu, P. Y., Xu, L., Zhang, H., & Cui, X. (2020). Hybrid model for estimating the shielding effectiveness of empty metallic enclosures. *IET Science, Measurement & Technology,* 14(8), 897–905. DOI: 10.1049/iet-smt.2019.0278

[48] Smith, A. R., Johnson, M. D., & Anderson, L. W. (2017). Electromagnetic compatibility design considerations for military electronic systems. *IEEE Transactions on Electromagnetic Compatibility,* 59(6), 1733–1743. DOI: 10.1109/TEMC.2017.2747440

[49] Kim, K. H., & Yang, S. H. (2017). Security issues and protection tech in military wireless communication networks. *CCNC.* DOI: 10.1109/CCNC.2017.7983261

[50] Abdul Rahuman, A. B., Priya, S., & Bhuvaneswari, K. (2019). Survey on asymmetric key cryptography algorithms. *ICOEI.* DOI: 10.1109/ICOEI.2019.8862501

[51] Liu, P. C. (2015). Physical security of electronic equipment in defense applications. *HST.* DOI: 10.1109/THS.2015.7225317

[52] Meireles, R. S. L., et al. (2017). Study of physical security requirements for military environments. *IRIS.* DOI: 10.1109/IRIS.2017.8250117

[53] Smith, J. H. (2019). Physical security technologies for protecting critical infrastructures. *HST.* DOI: 10.1109/HST47167.2019.9032994

[54] Fiengo, R., & Adams, A. (2024). Testing and evaluation of modern radar systems. *IET Radar, Sonar & Navigation,* 18(9), 934–950. DOI: 10.1049/rsn2.12614

[55] Alkan, M., Karpat, A., & Karaoglanli, B. (2017). Comparative study on sheet metal bending processes for stiffened plate structures. *Journal of Mechanical Science and Technology,* 31(7), 3319–3325. DOI: 10.1007/s12206-017-0653-3

[56] Mitra, A., & Phadke, U. P. (2018). CAD of precision fixtures for machine tools: A review. *International Journal of Advanced Manufacturing Technology,* 97, 2559–2577. DOI: 10.1007/s00170-018-1761-7

[57] Hassan, H., et al. (2019). Heat□sink design and optimization: A review. *Applied Thermal Engineering,* 149, 113789. DOI: 10.1016/j.applthermaleng.2019.113789

[58] Zhang, L., Chen, H., & Wang, M. (2019). Virtual prototyping and testing for military electronic enclosure design. *SMC.* DOI: 10.1109/SMC.2019.8914600

[59] Serale, G., et al. (2018). Model predictive control (MPC) and digital twins: A review. *Energy and Buildings,* 141, 96–113. DOI: 10.1016/j.enbuild.2017.02.031

[60] Oliveira, F. M., Azadmanjiri, J., Wang, X., Yu, M., & Sofer, Z. (2023). Structure Design and Processing Strategies of MXene-Based Materials for Electromagnetic Interference Shielding. *Small Methods,* 7(7), e2300112. DOI: 10.1002/smtd.202300112

[61] Garriga, A. G., et al. (2019). A Machine Learning Enabled Multi-Fidelity Platform for the Design of Complex Engineered Systems. *ASME Journal of Mechanical Design,* 141(12), 121405. DOI: 10.1115/1.4044216

[62] Park, K. (2021). Advances in testing techniques for military electronics. *ICEIC.* DOI: 10.1109/ICEIC51217.2021.9369784

[63] Johnson, R., & Brown, T. (2016). Environmental considerations in military electronics design. *IEEE Transactions on Electronics Packaging Manufacturing,* 39(2), 141–150. DOI: 10.1109/TEPM.2016.2548478

[64] Kim, S., Lee, J., & Park, H. (2018). Design and application of rugged military electronic enclosures for extreme environments. *AP□S/USNC□URSI.* DOI: 10.1109/APUSNCURSINRSM.2018.8609037

[65] Lee, S., Kim, H., & Choi, K. (2019). Aesthetics in military electronic enclosure design: A case study. *ISCE.* DOI: 10.1109/ISCE.2019.8900987

[66] Shukla, V. (2019). Review of electromagnetic interference shielding materials fabricated by iron ingredients. *Nanoscale Advances,* 1, 1640–1671. DOI: 10.1039/C9NA00108E

[67] Choi, Y., Lee, H., & Yoon, K. (2016). Application of military electronics in UAVs. *IROS.* DOI: 10.1109/IROS.2016.7759617

[68] Choi, J., Kim, M., Kim, H., & Kang, S. (2019). A review on advanced cooling technologies for electronic components. *IJPEM□Green Technology,* 6(2), 335–353. DOI: 10.1007/s40684-019-00094-y

[69] Han, S. J., Kim, T. S., Kim, J. J., & Yoo, J. W. (2018). A review on the development of high□performance packaging technologies for electronic systems. *IJPEM□Green Technology,* 5(4), 553–569. DOI: 10.1007/s40684-018-0052-5

[70] Liu, F., et al. (2022). Seventy years of radar–communications integration. *arXiv preprint.* DOI: 10.48550/arXiv.2210.00446

[71] Smith, J., Johnson, B., & Williams, R. (2017). Robust military electronic enclosures for harsh environments. *MILCOM.* DOI: 10.1109/MILCOM.2017.8170941

[72] Martinez, A., Johnson, S., & Davis, M. (2019). Design optimization of military electronic enclosures for size and weight reduction. *AP□S/USNC□URSI.* DOI: 10.1109/APUSNCURSINRSM.2019.8889181

[73] Hussain, S., Khan, M. R., & Kim, K. H. (2018). An overview of electromagnetic interference and compatibility in smart homes: Issues and challenges. *Sensors,* 18(5), 1581. DOI: 10.3390/s18051581

[74] Ross, I. M., et al. (2005). A hybrid optimal control framework for mission planning. *Journal of Guidance, Control, and Dynamics,* 28(4), 686–697. DOI: 10.2514/1.8285

Ass. Prof. Dr. Ahmet ATAK
Mechanical Engineer and Industrial Designer

After completing his Bachelor's and Master's degrees in Mechanical Engineering at Ruhr University Bochum in Germany and one year of preparatory courses in Bachelor's and Master's programs at Ankara Gazi University, he successfully completed his Ph.D. in the Department of Industrial Product Design in September 2019.

After working as a mechanical engineer for approximately 22 years in various companies in Germany, he returned to Turkey in early 2012. He worked as a Specialist Researcher at TUBITAK Space Research Institute for 5 years, followed by 2 years as the Structural Engineering Manager in the TAI Space Division.

From the beginning of 2020 until August 2022, he worked as an Assistant Professor at Gazi University TAI Kazan Vocational School. As of September 2022, he has been appointed as an Assistant Professor in the Industrial Design Department at OSTIM Technical University. He specializes in advanced design and analysis, design thinking, and systematic design methods, along with providing R&D consultancy in energy, medical, chemical facilities, and recently in the aerospace and space industries.