Secure Systems Design and Technology Development. Veliko Tarnovo, Bulgaria
Proceedings of the International Scientific Conference, 2026. Volume II, 97-102

From Conventional Camouflage Textiles to Metamaterial-Based Combat Protection: Review

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***Abstract*—This paper presents a conceptual review of the evolution of military camouflage systems from conventional textile-based concealment to advanced metamaterial-enabled multispectral protection. The study analyzes the current limitations of traditional camouflage materials in the face of modern detection technologies, including infrared imaging, radar systems, LIDAR platforms, and AI-assisted sensor fusion and automated target-recognition systems. Particular attention is given to metamaterial structures based on split-ring resonators (SRRs), transformation optics, coding metasurfaces, and adaptive electromagnetic shielding concepts. The paper discusses integrating conductive and resonant elements into textile architectures through embroidery, nanoprinting, and composite fabrication. Recent developments in self-healing polymers, omniphobic coatings, and adaptive thermal camouflage are also reviewed as emerging technologies for future combat equipment. The advantages, operational limitations, and engineering challenges of wearable metamaterial systems are critically evaluated. The study concludes that metamaterial-assisted combat gear is a promising direction for next-generation multispectral military protection, although significant challenges remain regarding durability, scalability, and battlefield implementation.**

***Keywords*— camouflage textiles, coding metasurfaces, electromagnetic shielding, metamaterials, multispectral protection.**

I. INTRODUCTION

Modern military operations require integrated protection systems capable of simultaneously addressing ballistic, thermal, chemical, and electromagnetic threats. Research on protective equipment encompasses various aspects of military clothing, including the development of functional textile structures, the optimization of garment components, and the improvement of camouflage coloration. Particular attention is given to protection against electromagnetic radiation by integrating conductive elements into textile structures, enabling shielding effects without significantly compromising flexibility and functionality [1].

Alongside the development of advanced textile structures for specialized applications, considerable research focuses on enhancing the protective and operational performance of military clothing. These approaches include incorporating nanomaterials to improve fabric properties, designing multifunctional composite systems [2], and developing advanced camouflage fabrics to enhance the effectiveness and functionality of combat uniforms in field conditions [3].

The evolution of military camouflage has closely followed advances in textile technologies and dye chemistry. The transition from brightly colored historical uniforms to modern digital camouflage is driven by a common objective: minimizing visual detection by adapting to the surrounding environment. Today, the digital transformation of defense technologies marks a new stage in protective equipment development, shifting from conventional passive camouflage to advanced, adaptive, and multifunctional systems. However, the emergence of multispectral sensing technologies has fundamentally changed the requirements imposed on camouflage systems.

This transformation responds to the rapid advancement of surveillance and detection technologies. In the contemporary operational environment, military personnel face threats beyond conventional visual observation. Modern detection systems include thermographic sensors, laser-guided targeting technologies, multispectral aerial surveillance platforms, and high-resolution radar systems. Consequently, a major challenge in developing military protective equipment is achieving effective concealment and survivability across multiple detection spectra, not just the visible spectrum. This paper is based on a structured literature review of recent advances in metamaterials, electromagnetic shielding textiles, and multispectral camouflage systems. The analyzed sources include experimental studies, theoretical models, and defense technology reports focused on split-ring resonators,

Online ISSN 3044-7771
https://doi.org/10.68302/std2026.vol2.172

transformation optics, coding metasurfaces, and wearable electromagnetic shielding structures.

This paper analyzes the technological transition from conventional camouflage textiles to metamaterial-based multispectral protection systems by critically reviewing current scientific developments and emerging defense applications.

II. THE TECHNOLOGICAL LIMIT OF TRADITIONAL SYSTEMS

In modern combat environments, rapid detection is often followed by immediate engagement. Conventional camouflage textiles have reached their functional limits because they mainly provide passive visual concealment. Their material properties limit effective modulation of thermal emissions and radio-frequency reflections, exposing the technological limits of traditional camouflage compared to new multispectral intelligence methods. Regardless of camouflage quality, thermal radiation from the body or radar reflections from conventional metal-textile models remain unchanged, as these models are primarily designed for visual concealment. In high-tech warfare, such methods are inadequate against drones and autonomous sensor systems [4], [5]. The main disadvantages of commercial fabrics are high thermal emissivity and lack of infrared (IR) thermal control. Additionally, the human body is a significant heat source, and traditional protective fabrics absorb and re-emit heat, creating a strong thermal contrast easily detected by modern thermal imaging cameras [6]. Recent developments highlight the growing importance of multispectral detection and counter-detection technologies. The widespread use of unmanned aerial systems, infrared sensors, and AI-assisted surveillance has significantly reduced the effectiveness of conventional visual camouflage. Modern detection systems in military scenarios integrate radar, thermal imaging, and multispectral analysis to enable high-precision target identification and tracking. As a result, traditional textile-based camouflage materials, which primarily provide passive visual concealment, are insufficient against integrated multisensor detection systems. These systems can reconstruct object geometry using radar- and LIDAR-based 3D sensing, even when visual concealment measures are effective in the visible spectrum. Metamaterial-based coatings and structured electromagnetic surfaces are therefore being investigated as potential solutions to reduce detectability across multiple spectral domains, including the microwave and infrared ranges. Unlike conventional materials, which lack engineered subwavelength resonant structures, metamaterial systems can be designed to actively manipulate reflection, scattering, and absorption characteristics of incident electromagnetic waves.

III. METAMATERIALS AND TRANSFORMATION OPTICS

Metamaterials represent engineered structures whose electromagnetic properties are primarily determined by subwavelength geometry rather than chemical composition. While conventional textiles exhibit limited optical and electromagnetic responses governed primarily by reflection and absorption, metastructured shielding systems can manipulate electromagnetic wave propagation through engineered effective permittivity and permeability distributions. This figure explains the two fundamental mechanisms by which metamaterials manipulate the electromagnetic spectrum.

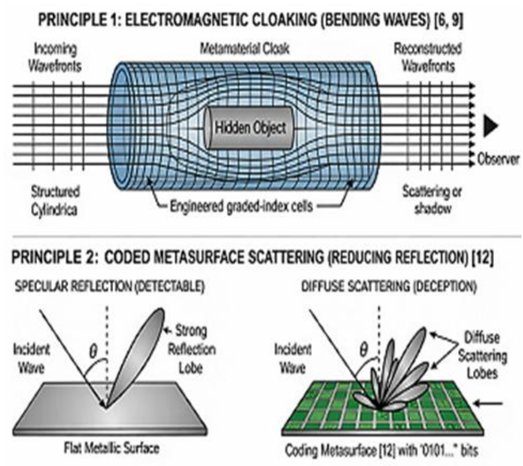

Fig. 1. Fundamental mechanisms of electromagnetic control in metamaterial systems: (a) wavefront bending principle for cloaking applications [7], [8]; (b) comparison between conventional specular reflection and programmable diffuse scattering in coding metasurfaces [9].

Figure 1 illustrates two complementary physical mechanisms used in metamaterial-based electromagnetic manipulation. The first mechanism relies on transformation optics to redirect incident wavefronts around an object, while the second employs programmable phase distributions to engineer controlled scattering patterns and reduce detectability.

Early studies identified several classes of engineered resonant materials capable of supporting negative-index electromagnetic behavior suitable for multispectral cloaking applications [7]. These developments demonstrated that electromagnetic wave propagation could be artificially redirected around protected objects, thereby establishing the engineering foundation for practical cloaking technologies. In the initial experimental technology transfer system [8], the metastructures were implemented on printed circuit boards. This first-of-its-kind laboratory success is fundamental to the current integration of resonators into textile frames using industrial embroidery and nano-printing. In short, the transition from rigid laboratory prototypes (constructed on printed circuit boards) to individualized real-world protection is facilitated by injecting meta-elements directly into the textile matrix. For example, through computerized embroidery with metalized threads and direct nano-printing, complex geometries of ring resonators are embedded in the underlying fabrics, preserving ergonomics and tactical comfort. The transition from rigid laboratory-scale metastructures fabricated on printed circuit boards toward textile-integrated systems has enabled the development of flexible wearable electromagnetic shielding architectures. Contemporary fabrication approaches include conductive embroidery, nano-printing, and the direct integration of split-ring resonators (SRRs) into textile matrices, all while preserving flexibility and ergonomic performance.

Foundational studies by David R. Smith and co-workers [10], [11] demonstrated experimentally and theoretically that artificially engineered structures can exhibit negative refractive index behavior. Due to this physical property, metastructures not only interact with incident radiation but also can be engineered to manipulate the phase and amplitude distribution of incident electromagnetic waves. To describe the far-field scattering response of a coding metasurface, the following generalized expression can be used:

$$f(\theta,\varphi) = f_e(\theta,\varphi)\sum_{m=1}^{N}\sum_{n=1}^{N} \mathrm{e}^{-i\left[\Phi(m,n)+kD\sin\theta\left(\left(m-\frac{N+1}{2}\right)cos\varphi+\left(n-\frac{N+1}{2}\right)\sin\varphi\right)\right]} \quad (1)$$

where:

- f(θ,ϕ) - the far-field scattering function;
- fe(θ,ϕ) - the element radiation pattern;
- Φ(m,n) - represents the programmable phase response of the (m,n) metasurface element;
- k - the electromagnetic wave number;
- D - the periodic spacing between adjacent metasurface elements;
- θ -12 the observation angles in spherical coordinates.

The equation indicates that the far-field scattering response of the coding metasurface is governed by the spatial phase distribution Φ(m,n) imposed across the metasurface elements. Through engineered phase modulation of the metasurface elements, electromagnetic waves can interfere destructively in selected directions, resulting in the suppression of specular reflection and a significant reduction in radar cross-section (RCS) [9].

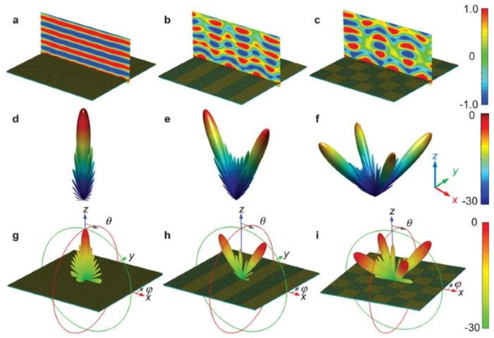

Fig. 2. Numerical simulation of electromagnetic wave scattering in coding metasurfaces [9]: (a–c) electric field distribution; (d–f) far-field radiation patterns; (g–i) three-dimensional scattering redistribution.

Numerical simulation results of electromagnetic wave scattering from coding metasurfaces [9]: (a–c) electric field distributions; (d–f) 3D far-field radiation patterns demonstrating controlled scattering redistribution; (g–i) full 3D visualization of diffuse electromagnetic scattering for passive radar deception and radar cross-section (RCS) suppression.

IV. TECHNOLOGICAL INTEGRATION AND APPLICATIONS

The use of geometries such as hexagonal or decagonal resonators helps precisely manipulate the electromagnetic response of equipment to microwave radiation [12], leading to significantly improved shielding effectiveness, ranging from 6 dB to 15 dB [13]. Modern advances enable the integration of meta-elements into textile structures using conductive threads (stainless steel or silver) applied via industrial embroidery. This addresses the key tension between functionality and ergonomics, allowing the material to retain porosity and mechanical adaptability while the embedded periodic array of resonators actively controls the object's radar signature. Such hybrid systems turn the uniform into an active element of contribute to passive electromagnetic signature management. Similarly, technologies such as „Lenticular metasurfaces for passive deception" [9] offer a practical approach for adapting to this new environment. Using lenticular optical lenses, these systems refract visual space, distorting or reducing visual signature perception under selected observation conditions. The current stage of military technology marks the transformation of a single combat unit from a simple concealment system into an active interface for multispectral protection. This transition reflects the evolution of camouflage systems from passive visual concealment toward adaptive multispectral signature-management technologies [14].

Applying the principles of transformation optics, the energy flow is channeled and contoured around the protected object, thereby shielding it from detection by multispectral sensors. The physical realization of this process, in which resonant elements are embedded in the textile matrix, is illustrated in Fig. 3.

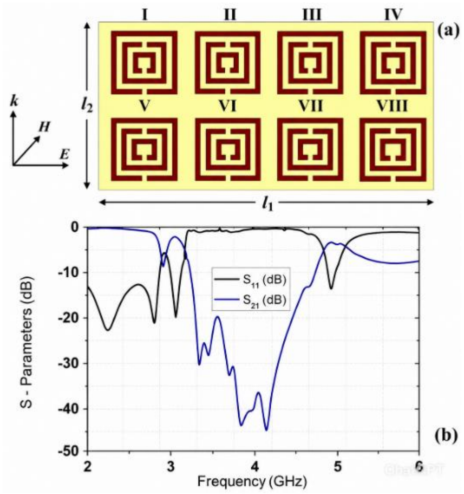

Fig. 3. Textile-integrated SRR-based metamaterial composite structure with conductive embroidery and periodic resonant elements [13].

Figure 3 demonstrates the practical implementation of split-ring resonators embedded into textile-compatible substrates. The conductive network enables controlled interaction with incident electromagnetic waves, supporting radar cross-section reduction while preserving mechanical flexibility.

The integration of metamaterial-based armor systems with ballistic protection technologies represents a fundamental shift in the concept of military survivability. Future protective systems are expected not only to provide conventional camouflage but also to significantly reduce the optical, infrared, and electromagnetic signatures of personnel and military platforms, thereby limiting detectability by advanced sensor systems. Recent studies have demonstrated the feasibility of flexible metamaterial layers for integration into personal protective systems and armored vehicles. These adaptive structures enable dynamic manipulation of electromagnetic wave propagation in both the visible and microwave spectral regions, allowing objects to partially match their surrounding environment and reduce detectability under multispectral surveillance conditions [15].

In parallel, nanostructured surfaces for adaptive thermal camouflage have been developed to emit controlled infrared radiation that simulates the thermal characteristics of the surrounding environment. Such systems reduce infrared contrast and thermal detectability, contributing to the development of low-observable military platforms capable of operating under continuous electronic, optical, infrared, and radar surveillance.

V. CHALLENGES TO OPERATION

Despite significant advances in metamaterial engineering, the practical implementation of wearable metamaterial systems in extreme battlefield conditions remains a major challenge. The electromagnetic behavior of metamaterials depends on subwavelength precision and geometric periodicity of their resonant structures, called "meta-atoms." Repeated bending, abrasion, mechanical deformation, and long-term wear may significantly affect their electromagnetic performance and structural stability. In real battlefield environments, contamination by dust, mud, moisture, oils, or other particles may alter the local dielectric properties of the metasurface. These changes can cause unwanted thermal anomalies may alter local electromagnetic boundary conditions and generate detectable thermal or electromagnetic inconsistencies. Maintaining the functional stability of metamaterial-based camouflage under operational conditions is therefore a major engineering challenge for the development of next-generation combat equipment.

Another important limitation concerns maintenance and durability. Conventional chemical cleaning and thermal treatments may irreversibly damage delicate nanostructured layers and reduce shielding efficiency. Current research focuses on omniphobic and self-cleaning protective coatings that preserve electromagnetic functionality during repeated washing and prolonged exposure to the field [16].

Additional progress has been achieved through the development of hybrid textile composites in which metastructures are encapsulated within elastomeric protective matrices or directly integrated into textile fibers. Such encapsulation strategies improve mechanical durability, environmental resistance, and long-term operational stability while preserving multispectral shielding capabilities and ballistic protection performance [17].

VI. Multifunctional Metamaterial Architectures for Adaptive Electromagnetic Camouflage and Signature Management

The implementation of metamaterial structures with negative refractive index properties (n<0) marks a significant transition from conventional passive camouflage toward active electromagnetic signature management. Through the precise design of resonant meta-atoms integrated into protective systems, modern combat equipment can enable engineered manipulation of the propagation, reflection, and scattering of electromagnetic waves across multiple spectral ranges.

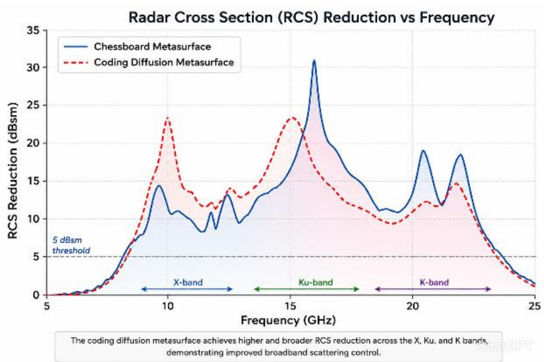

Fig.4 Comparison of electromagnetic wave scattering from a traditional metal surface (left) and a digital sequence encoding metasurface (right).

Figure 4 illustrates the difference between electromagnetic wave scattering from a conventional metallic surface and from a coding metasurface with programmable phase distribution. Unlike traditional reflective surfaces, the metasurface redistributes electromagnetic energy diffusely, thereby reducing radar cross-section (RCS) and enhancing passive sensor deception capabilities [9].

This technological approach enables the development of multispectral protection systems that reduce detectability across the infrared, visible, and microwave spectral regions. The integration of electromagnetic functionality with advanced ballistic protection represents one of the central engineering challenges in modern defense materials research. In particular, the combination of wave-manipulation capability with high mechanical durability requires the development of hierarchical composite architectures and multifunctional nanostructured materials.

Recent advances in hierarchical nanocomposites, adaptive polymers, and self-healing materials have enhanced the structural stability and operational durability of metamaterial-based protective systems under mechanical and ballistic stresses. Such technologies may enable future combat equipment to maintain both mechanical integrity and electromagnetic performance during prolonged operational deployment.

The reviewed studies demonstrate that metamaterial-assisted protection systems have the potential to significantly improve multispectral concealment and reduce vulnerability to advanced surveillance technologies, including radar, infrared imaging, and AI-assisted sensor platforms [5]. As a result, modern camouflage concepts are evolving from passive visual concealment to adaptive, multifunctional protection systems capable of dynamically controlling electromagnetic signatures.

VII. CONCLUSION

The reviewed literature shows that military camouflage is evolving from conventional passive concealment to adaptive multispectral protection systems that control electromagnetic signatures across multiple spectral domains. Traditional camouflage textiles remain effective for visual blending, but have limited ability to regulate infrared emission, radar reflection, and electromagnetic scattering. This significantly reduces their effectiveness against modern multisensor surveillance technologies such as radar, thermal imaging, LIDAR, and AI-assisted detection systems.

Metamaterial-based architectures offer an effective alternative by integrating engineered resonant structures that manipulate the propagation, absorption, reflection, and scattering of electromagnetic waves. Technologies based on split-ring resonators (SRRs), coding metasurfaces, and transformation optics show considerable capability to reduce radar cross-section (RCS) and infrared detectability while maintaining the flexibility and wearability required for combat equipment.

Integrating conductive as well as resonant meta-elements into textile structures through embroidery, nanoprinting and hybrid composite fabrication is an important step towards wearable electromagnetic shielding systems. Recent advances in hierarchical nanocomposites, adaptive polymers, self-healing materials, and omniphobic protective coatings have also improved the durability, environmental resistance, and functional stability of metamaterial-enabled combat textiles under realistic combat conditions.

In spite of these advances, several major challenges persist, including large-scale manufacturability, long-term mechanical reliability, preservation of electromagnetic performance under deformation and environmental contamination, and integration of multispectral protection with ballistic and ergonomic requirements. Additional interdisciplinary research combining materials science, textile engineering, nanotechnology, and electromagnetic design is needed before widespread battlefield implementation becomes feasible.

Overall, metamaterial-assisted protection systems constitute a major technological direction for advanced military equipment. Their future development may enable lightweight, adaptive, and multifunctional combat platforms capable of dynamically managing electromagnetic signatures while simultaneously providing mechanical protection and operational survival in complex multispectral combat settings.

ACKNOWLEDMENT

National Scientific Program – Security and Defence is funded by the Ministry of Education and Science of the Republic of Bulgaria in the implementation of the National Strategy for the Development of Scientific Research 2017-2030 and was adopted by Decision of the Council of Ministers No. 731 of October 21, 2021.

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