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Materials for Soldier Camouflage – Congressional Report for PE 622143.AZ5.03 (FY21) (Summary Technical Report, Oct 2020– Sep 2021)

by James M Sands, Matthew S Bratcher, and Mark H Griep

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14. ABSTRACT This is a Summary Technical Report on technology innovation and advancement completed by the US Army Combat Capabilities Development Command Army Research Laboratory and collaborators from Oct 2020 to Sep 2021 under FY21 program element 622143.AZ5.03 <i>Energy Coupled to Matter</i> (\$2.99 M). The focus was sharpened on tactical program needs for the Warfighter by leveraging the technology innovations from this program element. In this report, the authors summarize the technical developments and equipment positioning for delivering to the Army a suite of solutions for the protection of Soldiers on the battlefield through designing advanced camouflage capability. While the report is open domain, the technology that underpins the concepts are general and applicable across multiple platforms and dual-use applications. So, the report describes the basics of materials characterization, testing, measurement methods, and objectives for achieving new capabilities in this research domain.					
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Contents

List of Figures	iv
Summary	v
1. Mission Description	1
2. Research Goals	1
3. Program Objective	2
4. Current State of the Art	6
5. Research Accomplishments	6
6. Findings/Outcomes	9
7. Major Partners	10
8. Recommendations	10
9. Payoff/Army Impact	11
10. Publications	12
11. References	13
List of Symbols, Abbreviations, and Acronyms	14
Distribution List	16

List of Figures

Fig. 1	To touch the complexity of signature control for a dismounted Soldier, one must address the relationship and interactions of the EM spectrum (VIS, NIR, and SWIR) mapped onto the Soldier in a multidomain operational environment	4
Fig. 2	Cartoon depiction for response in a tunable MS reflector with varying degrees of stress applied to a flexible substrate	7
Fig. 3	Demonstration of mapping the MS/BR into the tunable color map for quantification across the color spectrum.....	7

Summary

This report documents the readiness of the Army to deliver technical outcomes for two key research thrusts in support of materials for Soldier camouflage. In particular, the research programs are notionally divided into two subcategories: 1) color-changing materials and 2) concealment concepts and applications. The specific separations around these categories is to establish basic science principles in both areas while allowing separation of information flow for transitional research that begins to fall under controlled flow of information management tools. Because the importance of harvesting the technical expertise in our academic and industrial leaders in the United States is a critical component of accelerating the successful outcomes, the program structure enables effective collaborations in materials formulation, characterization, and design of devices without invoking signature control features. The rest of the program research, as it begins to target Soldier-relevant form factors or address key parts of the electromagnetic spectrum, can be harvested separately to protect the end user and the tenant agencies seeking to deploy the technology for protective measures in the future. The funding to underpin this project initiation was provided through program element *622143.AZ5.03 Energy Coupled to Matter (FY21)*.

The color-changing materials program identified critical research steps that can demonstrate effectiveness of material conceptually toward protecting the Warfighter in the battlefield. The research program will develop both new color-changing materials and new machine-learning-based design methodologies required for optimization of relevant materials to support dismounted Soldiers under the Soldier Lethality and Protection Cross-Functional Team. Experimental and simulation data sets generated through these materials' development efforts are used to train machine learning and neural network models, facilitate design generation based on end-user requirements, and optimize color-changing materials to specific application requirements. Concepts will be closely partnered with multiservice Department of Defense (DOD) signature management subject-matter experts (SMEs) to assure relevance and tasks are carried out at the unclassified level.

Concealment concepts and applications components of the program will specifically seek to address military relevance of the color-changing materials. Research efforts will create new advanced multispectral materials to conceal dismounted Soldiers from enemy detection and include material designs for 1) individual dismounted Soldiers, 2) small arms, 3) Soldier-carried field equipment, and 4) Soldier-deployable remote devices. The conceptual strategy focuses on a layered approach to combine conventional signature-reduction

techniques with falsification and decoys over a very broad electro-optical sensor range. This approach significantly degrades the enemy's confidence in their imaging systems and conceals our force's location, size, strength, and capabilities to provide US forces increased time until detection resulting in the ability to strike first, strike closer (increased lethality), and avoid directed fire (protection). The program includes a range of developmental maturity levels to address immediate and long-term future threats and includes close collaboration with multiservice DOD signature management SMEs to assure relevance, user buy-in, and platform transition.

1. Mission Description

The Soldier's mission is diverse and involves multidomain operations at the theater level. To enable Soldier performance to be maintained across the varied theater conditions, an adaptable capability that responds to the environment or the ability to tune responses of the Soldier's equipment to match the environment are critical. The present research function will develop the materials solutions that support the adaptable Soldier equipment for environments anticipated in the future fight. The reasoning for seeking this mission work is to avoid conflicts with classification guides, where actively managed changes to respond to an environment are specifically managed by a proponent and their security classification guide (SCG). Since the early 6.1 and 6.2 program investments are driven by materials response and performance, the purpose of the mission program is not to address the application-driven responses, but to fully understand materials and equipment performance in various environments and to optimize the materials technical value for mission engagement.

2. Research Goals

Emerging capabilities in the design and fabrication of nanophotonic structures has yielded numerous material concepts for customizable light-matter interactions. By designing subwavelength structures of select materials, such as in plasmonic metasurfaces (MSs), strong electromagnetic (EM) coupling can be achieved at frequencies across the visible spectrum. Tuning of the MS EM response can be achieved through modification of the substrate's structural design, material composition, and 2-D pattern layout. Within the patterning, we generated alterations in the pattern spacing that can lead to controlled modulation of the optical frequency spectrum and yield highly chromatic scattered colors encompassing large areas of the human vision spectrum. Due to the ability to generate near-pure colors, opportunities are presented to create a dynamic color palette that would allow for the controllable reflection of nearly any hue within the human color perception through strain-induced control of pattern spacing in real time. This work aims to enhance and enable MS color-changing concepts through the design, manufacturing, and understanding of color-sharpening mechanisms (near-field vs. far-field MS EM coupling designs) and color-mixing strategies through the integration of an EM-tunable Bragg reflector (BR) back plane. Experimental and theoretical approaches will be employed to understand and optimize the multivariate system to define the interacting roles of MS composition, pattern design, pattern spacing, and BR design toward selective color scattering and intensity.

In addition to the development of new material systems, the extensive data sets created through this effort provide a unique opportunity to generate and train deep neural network models, enabling the rapid generation of color-changing material designs tailored specifically to an end-user's application needs. Current approaches to MS design rely heavily on intuition based on previously studied concepts, with each design individually requiring iterative experimentation/modeling to optimize. Development of artificial intelligence algorithms based on our multivariate data sets can directly optimize material design parameters toward the application requirements and manufacturing constraints. Additionally, such algorithms could enable autonomous control of the color-changing material's response to the environment.

3. Program Objective

The program objective is to create a toolbox of new concealment materials specifically designed for dismounted Soldier applications. Currently, US fielded-Soldier concealment capabilities address only a small portion of the visible and infrared frequency domain. This research program strategically develops new multispectral materials to absorb, reflect, and alter the baseline signature of Soldiers. The materials provide control of how the Soldier is perceived by a wide array of battlefield sensors including the human eye and visible (VIS), near infrared (NIR), short-wavelength infrared (SWIR), mid-wavelength infrared (MWIR), long-wavelength infrared (LWIR) and up-through-the-ground surveillance radar. This necessitates creating a variety of material concepts, at various classification levels, to provide layers of adaptable protection from multiple-band sensor threats operating in a dynamic battlefield environment. Research will employ a combination of near-term solutions based on leveraging existing vehicle-based concealment material and concepts with investigating areas known to be of multiservice scientific interest for advancing the state of the art.

Specifics of research performance requirements fall under the low-observable/counter-low-observable (LO/CLO) SCGs and can be discussed in detail at the appropriate classification level. In general, research areas will include adaptation of multispectral vehicle coatings and fabric-based composites. These items are of interest because of their emission properties at relevant wavelengths. However, the form factors and weight constraints of the dismounted Soldier are unique and require reassessment of the form factors and risk-mitigation purposes (threats) related to these products.

Overall, research will focus on creating materials with higher LO modification performance capable of significantly altering detection and resulting in enhanced

battlefield dominance. Materials are developed specifically based on close collaboration with multiagency camouflage- and concealment-related offices and the US Army Combat Capabilities Development Command (DEVCOM) Soldier Center (SC) to support transition into Soldier-relevant articles and equipment.

Decoy and deception concepts will focus on using multispectral materials to modify signals perceived by enemy sensors to confuse and delay battlefield decision processes at a Soldier-relevant level. Current state of US capabilities will require initial conceptualization and research development. Decoy and deception under this program are materials-based but account for existing electronic-based systems to create integrated layered solutions as well.

The research will primarily focus on innovating and processing materials into relevant designs to deploy into demonstration-ready form factors. These demonstration concepts will inform the models and the simulation teams in how to use the materials solutions toward mission-enhanced performance and increased survivability of the Soldier across various theater-use cases. Such is the motivation and drive for the investments and teaming outlined in this report.

Figure 1 successfully demonstrates the breadth of spectral needs and the materials system that is predominant for Soldier operations. Because of the complexity of spectral variations, detection tools, and Soldier operating environments, the program needs to narrow the scope to materials focuses that are determined by collaborative understanding of these tools and operational needs.



Fig. 1 To touch the complexity of signature control for a dismounted Soldier, one must address the relationship and interactions of the EM spectrum (VIS, NIR, and SWIR) mapped onto the Soldier in a multidomain operational environment (image provided by DEVCOM SC)

The camouflage materials program is focused on two themes and tasks with specific outcomes to evaluate success.

1) Color-changing materials

a. Development of tunable MS/BR color-mixing materials

- i. Static MS response at three spectral positions around CIE 1931 color space
- ii. Stretchable MS at three base spectral positions around CIE 1931 color space
- iii. Reversible MS/BR for color mixing and color intensity control

- b. Deep learning neural networks for targeted response inverse design of hybrid system
 - i. Optical simulations of static MS with variations in metal (gold [Au], aluminum [Al]) feature spacing to span CIE 1931 color space, and feature shape
 - ii. Integration of experimental data into training of neural network for static MS and BR individual systems
 - iii. Demonstration of deep learning inverse design of MS/BR hybrids tailored toward user-specified field requirements
- 2) Concealment concepts and applications
 - a. Small arms concealment
 - i. Develop concepts and prototypes for small arms (SA) concealment
 - ii. Characterization and evaluation of coatings and prototypes
 - iii. Establish evaluation protocols for using foreign sensors
 - iv. Finite element analysis (FEA) model for SA concealment concepts
 - v. Design and fabrication of high-temperature composite prototypes
 - vi. Formulation of high-temperature coatings for SA
 - b. Deception/decoy concept development
 - i. Design and fabricate small arms decoy platform
 - ii. Laboratory evaluation of small arms decoy designs
 - iii. Develop data processing/tagging protocols
 - iv. Range test/evaluation

The critical state of these studies to date is reported subsequently. However, much of the detail is not within the scope of release appropriate for this report. Interested reviewers with appropriate need to know are welcome to reach out to the US Army Combat Capabilities Development Command Army Research Laboratory for follow up of relevant content areas of interest.

4. Current State of the Art

Expanded capability significantly enables the completion of the mission by establishing the baseline performance of the materials and the comprehensive connection between the materials and the sensor suites related to field response. DEVCOM Army Research Laboratory has acquired resources (sensors, computer algorithms, and materials) that connect materials data through devices to generate data and subsequent analysis. The raw data is coupled with modeling tools that enable collaborative exchange between the ideation of response and the physical performance of materials in the environment. This represents an upgrade to state-of-the-art sensor capability and predictive capability within the laboratory setting, allowing rapid decision-making processes on the strategic directions to invest the available 6.1 and 6.2 program dollars.

5. Research Accomplishments

The research accomplishments will be primarily reported in Area 1 of the program for sensitivity reasons. However, the summation of focus product outcomes in the Area 2 program will be highlighted.

A key to achieving a materials toolbox for this area is the ability to establish materials performance characteristics of relevance. To this end, DEVCOM ARL demonstrated static and agile color tunability with a range of material solutions. The primary study element included the MS/BR field where the incorporation of the processing and materials know-how led to a successful integration of MS onto a flexible BR. This achievement is an essential milestone in the path forward as, unlike in vehicle operations, Soldier system solutions must be adaptable to the Soldier's shape and movement. The ability to demonstrate the materials' concepts in the MS/BR opens significant advancement options for the 6.1 program. In addition, the team expanded the modeling capabilities and verified predictions for BR solutions. Collaborators in the academic communities are key to developing the tools to demonstrate responses in a quantifiable manner, as shown in Fig. 2.

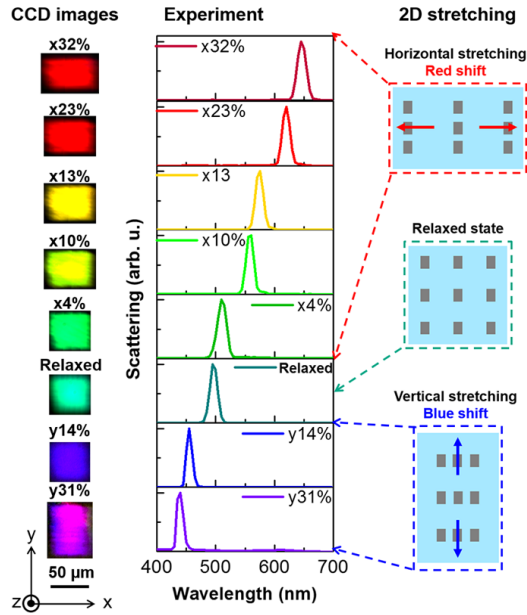


Fig. 2 Cartoon depiction for response in a tunable MS reflector with varying degrees of stress applied to a flexible substrate (Tseng et al. 2017)

Another successful outcome is in the determination of color identification, as shown in Fig. 3. The breadth of requirements and the quantification of performance are key metrics to the visual portion of camouflage. Because the industry is driving toward limited visual schemes (think hunting applications where visual obscuration is from an animal), the technology for quantification in the market is somewhat limited. As the program started up, we sought to enhance the spectral discretization and discretization that could be accomplished in the color frequencies of interest. The tools are now part of the suite of available elements for comparisons of materials' response. The tool set also offers the ability to look at angle-based discrimination of color, which becomes relevant on flexible surfaces but deviates from the industry need for vehicle evaluations.

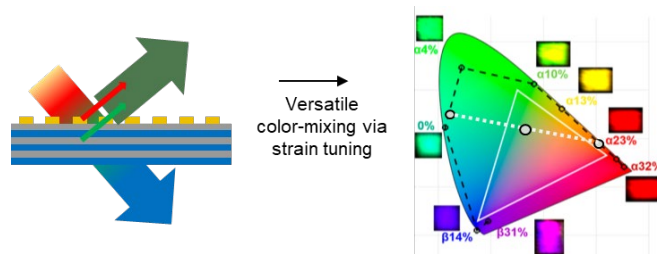


Fig. 3 Demonstration of mapping the MS/BR into the tunable color map for quantification across the color spectrum

Optical simulation has been initiated in this program to provide direction for the broad spectral research products. In optical simulations of static multispectral

simulations, researchers identified that variations in metals (Au, Al) and in feature spacing enable the span of CIE 1931 color space to be achieved. In addition, researchers can optically explore the influence of feature shape or spectral response along specific lines of sight, a critical part of managing observer information at a relevant distance. The initial scope of work in optical simulation sought to benchmark the research field around three static spectral positions (red, green, and blue) around the CIE 1931 color space. However, upon completion of the survey it became evident that greater fidelity would be necessary to make decisions and narrow the scope of research content in multispectral space.

The research team focused initial simulations of static BR design around variations in layer thickness, layer numbers, and refractive index differences between layers. Again, initial surveys explored three critical constructs, but results yielded greater need to expand model fidelity and enable predictive tools to be deployed in analysis of data groups. Hence, expanded modeling efforts were begun and are a focus of ongoing developments.

Because data streams will be significant in this research program, efforts shifted toward training of neural networks with optical simulation data for predictive design of static MS and BR individual systems. The use of powerful neural network processing strategies will enable researchers to make critical evaluations of large data sets while quickly identifying synthetic strategies that will enable producing relevant structures and designs. A key to success will be the correlation between these data sets and the outcomes. In early experimental comparisons, the research teams identified that accuracy of optical simulations was enhanced significantly when the model inputs were specific and measured rather than generalized data from tables or handbooks. So, researchers will focus on making experimentally accurate measures in key parameters such as refractive index (including temperature-related shifts) and other key parameters to help refine the model sets prior to deploying neural network codes to analyze and refine the design optimization.

The work related to concealment concepts for the program was to generate measurement baselines and assemble tools to produce meaningful decision points. Several experimental capabilities were installed that support the program in evaluating thermal environments. Specifically, the team acquired tools that can measure response in the VIS to NIR, SWIR, MWIR, and LWIR. Upon assembling the tools, the team set about experimentally creating baseline performance of industrially available materials of specific and general interest, evaluating more than 50 materials. These baseline results are essential for bounding the research tools' quantification potential (if they are able to discriminate materials responses and allow decisions, and what characteristics are observable), as well as the

operator's performance limits. Each of the technologies has complexities that will make operator variables important to establish comparative data sets and the ramp-up effort established an uncontrolled data set for training and performance to be generated across multiple spectral frequencies.

Once successfully bounding the performance, a case study was undertaken to assess thermal detectability of a notional suppressor that might be found deployed on a Soldier's shoulder-fired weapon. The ability to explore thermal management on a real-world shape and relevant equipment case brought forth key questions that will lead the program into determining pass/fail criteria on designs that were not appreciated prior to experimentation and case analysis.

6. Findings/Outcomes

- Fano design created for scalable manufacturing approaches
- Demonstrated color tunability corresponding to alteration in MS periodicity
- Flexible BRs created that allow color tunability across the visible spectrum
- Integration of plasmonic MS with BRs for coupled reflected color response
- Numerical modeling capabilities established and optimized to perform near-field analysis in under 10 min
- MatLab code developed for image and spectra translation into select color coordinates
- Standardized light source (tunable to select environment) and fiber-optic color measurement tools (>1 mm² samples) developed and installed
- Acquired and installed new capabilities for performing quantitative evaluations of materials in VIS/NIR, SWIR, MWIR, LWIR and characterized >50 commercially available materials
- Developed comprehensive technical work flow to assess materials/concepts
- Demonstrated initial success on suppressor application
- Developed FEA model for suppressor to design prototype where coatings reduced thermal signature (80 °C change) after 60 round bursts

7. Major Partners

- Fibrotex (Stearns, KY): Develops camouflage-netting products such as ULCANS. They have a strong relationship with Program Manager (PM) Force Sustainment Systems, which is part of PEO CS&CSS.
- DEVCOM SC (Natick, MA): Subject-matter expertise includes PM Force Sustainment Systems, camouflage-netting development, and Soldier Lethality (SL) Cross-Functional Team (CFT) Leader advising on priorities for concealment/camouflage solutions for the Soldier.
- NSWC-D (Dahlgren, VA): Team is leading the effort to integrate intelligent tracking technology into the Next-Generation Combat Vehicle and can use our field test data to help train the target tracking algorithms.
- C5ISR-NVSED (Belvoir, VA): Facilitated transfer and training on the Night Vision Integrated Performance Model for program staff.
- 3M (St Paul, MN): Materials supplier and technical leaders in automotive window films and thermal barrier materials.
- University of Massachusetts at Amherst (Amherst, MA), Center for Hierarchical Manufacturing (CHM): The CHM is a leading research/education center for the development of advanced manufacturing capabilities across multiple length scales. They are developing scalable nanofabrication routes of nanoimprint lithography and roll-to-roll manufacturing.
- Rice University (Houston, TX): Smalley-Curl Institute and Laboratory for Nano-photonics is a leader in the field of plasmonics and nanophotonics.

8. Recommendations

It is recommended to expand investments to incorporate active materials where appropriate and engage external collaborators strongly to acquire the materials supply chain necessary to advance the science. DEVCOM ARL will successfully demonstrate the concepts but to fully realize the performance benefits, materials from the industrial and academic infrastructures are essential. To complete the tasks toward relevant mission products, the team must operate within appropriate classification guides for disclosure. To manage the multispectral breadth of information, a team should be established to evaluate the risks of information release as it specifically relates to this market, as the complexity of information sharing to gain access to materials supplies and the experimental results can lead to

some challenges for the science community who desires to build networks of collaborators through information exchange.

9. Payoff/Army Impact

The color-changing materials research provides the capability to rapidly alter the color of the US Soldiers and associated equipment, enhancing Soldier survivability through reduced detectability by adversaries and increasing SL by enabling the Soldier to approach adversaries at shorter distances as well as obtain the element of surprise on adversaries. The breadth of impact in this area is beyond the local scope of technical performers alone and therefore is naturally driven toward collaborations with the broader research community. The internal programs are focused specifically on color shifts that can be effected through design of templates or through mechanically shifted changes related to flex and stretch of substrates (hence not mechanically or electrically driven changes). This focus is idealized toward the dismounted Soldier because Soldier-wearable equipment and protective gear establishes a different set of performance needs and performance opportunities compared to structural platforms, such as ground vehicles, robotic assist platforms, and drone technology.

The concealment concepts and applications research enable the community to build Army research infrastructure and capabilities toward SL CFT “Invisible Soldier” product needs and deliver decision points to Warfighter counsels on signature mission protocols. In addition, the research enables specific mission-related exchanges of ideas to be performed outside of the critical path to deployment and allows the tools to be exercised to assess relative performance gains in various approaches to protection using multispectral analysis and measurement methods. Enabling the Warfighter to build confidence in the technology and producing robust and data-driven solutions is paramount to increasing the protective posture, whether because of reduced detection thresholds or enhanced obscuration and deception methods. Each of these has key scientific growth opportunities and is explored in measures as determined by a customer-driven need.

10. Publications

Cerjan B, Gerislioglu B, Link S, Nordlander P, Halas N, Griep M. Towards scalable plasmonic fano-resonant metasurfaces for colorimetric sensing. *Nanotechnol.* Submitted 2022.

Cerjan B, Renard D, Link S, Halas N, Griep M. Electrophoretic deposition of aluminum nanoparticles through a nanopatterned resist. DEVCOM Army Research Laboratory; 2020. Report No.: ARL-TR-9007.

D'Archangel J, Cerjan B, Deguzman L, Griep M, Boreman G. Spectroscopic ellipsometry of thin film cyclic olefin copolymer for long-wave infrared metasurfaces. *Opt Mater Express.* 2021;11(11):3688–3696.

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DEVCOM Soldier Center. Personal communication between author and Mr John Kirejczyk. Image approved for public release, 24 Mar 2022.

Tseng ML, Yang J, Semmlinger M, Zhang C, Nordlander P, Halas NJ. Two-dimensional active tuning of an aluminum plasmonic array for full-spectrum response. *Nano Lett.* 2017;17(10):6034–6039.

List of Symbols, Abbreviations, and Acronyms

2-D	two-dimensional
Al	aluminum
ARL	Army Research Laboratory
Au	gold
BR	Bragg reflector
C5ISR	Command, Control, Communications, Computers, Cyber, Intelligence, Surveillance and Reconnaissance
CFT	cross-functional team
CHM	Center for Hierarchical Manufacturing
DEVCOM	US Army Combat Capabilities Development Command
DOD	Department of Defense
EM	electromagnetic
FEA	finite element analysis
LO/CLO	low observable/counter low observable
MS	metasurface
MWIR	mid-wavelength infrared
NIR	near infrared
NSWC-D	Naval Surface Warfare Center–Dahlgren
NVSED	Night Vision and Electronic Sensors Directorate
PEO CS&CSS	Program Executive Office, Combat Support and Combat Service Support
PM	Program Manager
SA	small arms
SC	Soldier Center
SCG	security classification guide
SL	Soldier Lethality

SME	subject-matter expert
STR	Summary Technical Report
SWIR	short-wavelength infrared
VIS	visible

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