
2019-2020
ASSESSMENT OF THE ARMY
RESEARCH LABORATORY

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DETAILS

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ASSESSMENT OF THE ARMY RESEARCH LABORATORY

Army Research Laboratory Technical Assessment Board

Laboratory Assessments Board

Division on Engineering and Physical Sciences

A Consensus Study Report of

The National Academies of
SCIENCES • ENGINEERING • MEDICINE

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Acknowledgment of Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Neil G. Siegel, NAE, Northrop Grumman Corporation (retired). He was responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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APPENDIXES

Summary

The statement of task that guided the work of the Army Research Laboratory Technical Assessment Board (ARLTAB) is as follows:

> The National Academies of Sciences, Engineering, and Medicine will appoint a committee to be named the Army Research Laboratory Technical Assessment Board (ARLTAB), to be overseen by the Laboratory Assessments Board (LAB), to continue the function of providing assessments of the scientific and technical quality of the research at the Army Research Laboratory (ARL). The committee will develop a series of reports that summarize the ARLTAB's findings, conclusions, and recommendations related to the quality of ARL's research programs.
>
> Every two years, the committee will assess six portions of the ARL technical program (three in year 1, three in year 2). To conduct its assessments the ARLTAB will be assisted by up to six separately appointed panels. The assessment completed in Year 1 will be released as an interim assessment report, which will be combined with the second year's assessment as a final biennial report.
>
> The committee will also review the extramural basic research programs at the Army Research Office (ARO), a subdivision of the ARL. Each year the ARLTAB will be supported by an additional panel that will focus on selected ARO programs, and the ARLTAB will annually provide a separate assessment report.
>
> While the primary role of the ARLTAB is to provide peer assessment, it may also offer advice on related matters when requested by the ARL Director.

During the 2019-2020 assessment, the ARLTAB is being assisted by four panels, each of which focuses on a portion of the program of the Combat Capabilities Development Command (CCDC) Army Research Laboratory (ARL) of the U.S. Army Futures Command's (AFC) CCDC. ARL's research core competencies include network and information sciences, computational sciences, human sciences, materials and manufacturing sciences, and propulsion sciences. A fifth panel to assess the ballistic sciences and protection sciences research core competencies will conduct it assessment in 2022, because the planned in-person 2020 meeting of the panel could not take place owing to COVID-19. Its meeting could not be conducted virtually because the research in ballistic sciences and protection sciences areas involved controlled unclassified information and classified information. For the extramural basic research programs at the Army Research Office (ARO), a subdivision of the ARL, each year the ARLTAB is supported by an additional panel that focuses on selected ARO programs, and the ARLTAB annually provides a separate assessment report.

This report summarizes the findings of the board for the 2019-2020 biennial assessment. This report subsumes the findings of the interim report[1] and adds the findings from the second year of the review. Because a full spectrum of projects and programs within each ARL campaign and the interrelated mapping across all campaigns' projects and programs were not provided to the ARLTAB, this report presents the board's assessment of only the projects and programs presented and is not intended to portray a representative assessment of the science and technology (S&T) work across ARL.

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[1] National Academies of Sciences, Engineering, and Medicine, 2020, *2019-2020 Assessment of the Army Research Laboratory: Interim Report*, Washington, DC: The National Academies Press, doi: https://doi.org/10.17226/25819.

The board examined the following elements within the ARL research core competencies:

- *Network and Information Sciences*—information sciences, networks, and cyber.
- *Computational Sciences*—computational sciences and atmospheric sciences.
- *Human Sciences*—human-autonomy team interactions and humans understanding autonomy, autonomy understanding humans and estimating human-autonomy team outcomes, human interest detection, cyber science and kinesiology, neuroscience, training effectiveness, and strengthening teamwork for robust operations with novel groups (STRONG).
- *Materials and Manufacturing Sciences*—optical sciences and photonics, electronics and optoelectronics, and energy science.
- *Propulsion Sciences*—platform power, platform design and control, and intelligent maneuver.

The U.S. Army CCDC ARL is the Army's corporate research laboratory strategically placed under the AFC. ARL is the Army's sole fundamental research laboratory focused on cutting-edge scientific discovery, technological innovation, and transition of knowledge products that offer great potential to improve the Army's chances of surviving and winning any future conflicts. The mission of ARL is to operationalize science for transformational overmatch. ARL has maintained its organizational structure, consisting of five directorates—Computational and Information Sciences Directorate (CISD), Human Research and Engineering Directorate (HRED), Sensors and Electron Devices Directorate (SEDD), Vehicle Technology Directorate (VTD), and Weapons and Materials Research Directorate (WMRD)—and the Army Research Office (ARO). The research portfolio has been organized into research core competencies, each of which describes related work supported by staff from multiple directorates. Appendix Table A.1 shows the directorates that supported each of the research core competencies during the 2019-2020 review.

ARL's vision is compelling and raises expectations for an innovative program of research designed to be responsive to the needs of the capabilities for the Army of 2030 and beyond. The reorganization of the portfolio into research core competencies is promising, but it may take some time to transform and mature the program of work to consistently align with the needs and capabilities for the Army of 2030 and beyond.

Four major changes to the Army and ARL clearly present challenges and promises to all research core competencies. These are the recent Army doctrinal changes to multi-domain operations (MDO), the reorganization that put ARL under the newly formed Army Futures Command (AFC), the divestiture of 6.3 work to other organizations,[2] and emphasis on "disruptive" technologies. Specifically, with the recent creation of the AFC, ARL has been charged to focus on foundational research; targeting—conducting research to drive change within, across, and between disciplines; creation of knowledge products for warfighting concept development of the future; and interacting with universities via the ARL Open Campus and the ARO.

In general, the quality of the research presented, the capabilities of the leadership, the knowledge and abilities of the investigators,[3] and proposed future directions continue to improve. Significant gains were

[2] Parsing research, development, test, and evaluation (RDT&E) funding by the character of the work, the Department of Defense (DoD) has established seven categories identified by a budget activity code (numbers 6.1-6.7) and a description. Budget activity code 6.1 is for basic research; 6.2 is for applied research; 6.3 is for advanced technology development; 6.4 is for advanced component development and prototypes; 6.5 is for systems development and demonstration; 6.6 is for RDT&E management support; and 6.7 is for operational system development.

[3] ARL has increased its civilian scientists and engineers (S&Es) with a Ph.D. degree from 434 to 688 from fiscal year (FY) 2006 to FY 2020. In FY 2020, 51 percent of its S&Es had a Ph.D. degree.

evident in publication rates,[4] numbers of postdoctoral and visiting researchers,[5] and collaborations with relevant peers outside ARL.[6] In this manner, ARL needs to continue to strive to perform research that has the potential to lead to disruptive technologies. The research work environments were impressive in terms of their unique and advanced technology capabilities to support research. Overall, these are outstanding accomplishments and mark an advance over prior years.

NETWORK AND INFORMATION SCIENCES

The research areas reviewed were information sciences and networks and cyber. The research projects under the banner of information sciences (IS) had a significant emphasis on artificial intelligence (AI) and machine learning (ML) as applied to diverse areas of Army relevance. Application areas included image understanding, automated language processing, augmented and virtual reality (AR/VR), and learning for control. There was a focus on multi-domain operations (MDO), and research projects were both foundational and disruptive, while maintaining Army relevance. There is a broad embrace of the transformative potential of AI and ML, especially in the context of how groups of people and autonomous systems can seamlessly collaborate, how technology can further aid with time-sensitive decision making in the presence of massive and diverse sources of information, and how virtual and augmented reality can be integrated in Army operations.

Research in the area of networks and cyber includes projects that fall into the general area of human-robot/machine interactions, with the two principal threads being scene narrative generation for humans by robots and robot learning from human demonstrations. This body of work is ambitious and has the potential to disrupt the way human-robot interactions are considered for future battlefields. Another important research methodology, especially for security issues, is to study systems that have both defense and offense techniques.

The research work in IS was assessed to be generally of high scientific quality, but not uniformly so. The research portfolio represents an appropriate balance of theoretical and experimental work, and many of the more mature programs—but not all—show a transition into practice or use by other areas. In most cases, the research projects reflected a good understanding of the problems being considered, an appropriate statement of the problem being pursued, a good knowledge of the appropriate methodologies to address the problem, and acquaintance with the state of the art and the relevant research pursued elsewhere. In many cases, the researchers are able to articulate Army relevance and identify research challenges that are unique to the Army's operational needs. The researchers are well-qualified to carry out the research problems that they are pursuing and follow rigorous research methodologies and practices. Many of the projects have already resulted in publications in highly visible journals and selective

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[4] For example, in CISD (where network cyber and information sciences and computational sciences and atmospheric sciences core competencies reside) for FY 2019, there were 56 journal publications and 168 conference publications. In HRED (where human sciences core competency resides) in the 2-year period from March 2017 to March 2019, there were 137 journal publications and 205 conference publications. In the materials and manufacturing sciences core competency area since 2017, there were 523 journal publications and 155 invited and keynote presentations. ARL had 1,121 scientists and engineers as of April 30, 2020.

[5] For example, in CISD for FY 2019 there were 27 visiting researchers.

[6] ARL had more than 515 active Cooperative Research and Development Agreements (CRADAs) with industry and academia as of June 18, 2019. Moreover, ARL's Open Campus Initiative was started in FY 2014 to link ARL with the global research community. The partners and ARL S&Es work side by side in research facilities. The collaborations are focused on Army-specific challenges of mutual importance to all partners. Partners from Army, industry, and academia engage in research with shared access to people, infrastructure, and resources. More information on ARL's Open Campus can be found at https://www.arl.army.mil/opencampus/, accessed March 2, 2020.

conferences. The computation facilities and instrumentation required are adequate to the needs of the researchers.

The overall scientific quality of the research in the networks and cyber was high, and comparable to research conducted at top research universities and government and industry laboratories. Researchers were very familiar with the underlying science and relevant leading research published and performed elsewhere. In many cases, there are active communications or collaborations with researchers outside ARL, many at the forefront of their respective fields. In all cases, the researchers were aware of the potential challenges, risks, and risk mitigations associated with their projects. In most cases, the researchers were able to incorporate these challenges, risks, and risk mitigations into their research. There is an appropriate balance of theory, computational work, and physical experimentation to inform and investigate multiple areas of research. The facilities and supporting infrastructure are well-suited for collaborative work. There is a good mix of well-trained research personnel who also collaborate with researchers in a broad range of academic and industrial partners in addition to working with the ARL South and ARL West regional sites. The research staff in this area have received outstanding recognition and awards for their research and technical contributions.

COMPUTATIONAL AND ATMOSPHERIC SCIENCES

Projects reviewed related to Battlefield Environment Division (BED) atmospheric observations and modeling and computational sciences research, considering both selected, in-depth research presentations and informal discussions surrounding research posters. Projects presented in depth spanned turbulence modeling in complex environments, using a lattice-Boltzmann computational model, understanding the influence of forest canopies on atmospheric dynamics on complex terrain, uncertainty quantification modeling for atomistic-scale modeling, and AI/ML at the edge implemented in field programmable gate arrays (FPGAs). In addition, posters spanned atmospheric model prediction via radar data assimilation, meteorological sensor arrays, aircraft vortex and rotor wake characterization, and ML characterization of particle shapes.

While daunting, the repurposing of the ARL mission also presents great opportunities to restate, revise, or create a new vision, which would allow scientists to reevaluate their individual programs in terms of how they fit into the new “big picture.” For some projects, the new MDO viewpoint was an immediate and natural fit, while for others, the connections between project objectives and MDO were still being developed. Broadly, the work presented was of high quality, comparable to that conducted at major research universities or leading-edge federal research and development (R&D) organizations.

Examples of this high-quality research include the hierarchical multiscale (HMS) project, which continues to break new ground in mission-relevant research, by maintaining and now extending its quality and utility from earlier reviews. Similarly, the AI project, using FPGAs, seeks to build capabilities into Army weaponry (beginning with gunsights), via a framework that involves software, customizable hardware, and reduced convolutional neural nets (CNNs) to meet space, weight, power, and time-to-solution constraints. Similarly, the work on ML to characterize particle shapes using scattered light images has the potential for wide applicability throughout aerosol science and in the broad area of chemical or biological agent characterization.

There are a few areas of opportunity. As an enabling, broad-based capability, the computational sciences and BED need to maintain a critical mass of expertise, both for targeted projects and for collaborative engagement with other projects. Similarly, the BED atmospheric modeling research is foundational for many MDO activities, but it would benefit from stronger connections to specific projects.

In turn, computational science is becoming a prominent element in training AI/ML systems, such as work using physics-based simulation engines from video games as the source of data to train autonomous vehicles. Further, many of the technical challenges in modern ML involve problems that have been well investigated in computational science work, and emerging research in academia and industry that involves substantive collaborations between computational science and AI/ML is increasingly seen. CISD is well-poised to catalyze important new work that involves collaborations between computational and information sciences, an area that does not currently appear to be pursued.

In summary, there is continued research progress, particularly engagement with academic stakeholders via ARL's distributed sites and collaborative academic projects. There is hiring and intellectual development of new postdoctoral associates and staff. ARL continues to foster collaboration across its internal organizational structure. Last, all projects would benefit from clearer metrics for research project success and associated project exit strategies, including transitions that maximize Army benefits.

HUMAN SCIENCES

The human sciences (HS) project areas reviewed were human-autonomy team interactions and humans understanding autonomy; autonomy understanding humans and estimating human-autonomy team outcomes; human interest detection; cyber science and kinesiology; neuroscience, training effectiveness, and strengthening teamwork for robust operations with novel groups (STRONG).

ARL's HS core competency is focused on identifying, creating, and transitioning scientific discoveries and technological innovations underlying three research areas: cognitive dominance, readiness for technological complexity, and teaming overmatch. These areas are critical to the U.S. Army's future technological superiority. This core competency area concentrates on high-risk and high-payoff transformational basic research with potential for having revolutionary impacts on the Army's warfighting capabilities. The ultimate goal is to contribute to the creation of disruptive and game-changing soldier-centric technologies for the Army, while also anticipating technological surprises from potential adversaries.

ARL needs to continue to focus on its long-term vision for advancing basic science research in human sciences. Its leadership needs to engage in more dialogue regarding its research strategies with its front-line researchers as well as the greater scientific community. An approach that incorporates both bottom-up and top-down approaches to advancing basic science research would strengthen the program and allow the ARL to advance its position to the forefront of basic research.

ARL continues to collaborate with universities through its state-of-the-art data collection facilities and through the STRONG program, with the goal of developing the foundation for enhanced teamwork within heterogeneous human-intelligent agent teams. Such continuing collaborations would develop the top talent needed among the next generation of researchers to realize ARL's long-term research vision for advancing U.S. Army capabilities and to broaden the pool of trainees familiar with the unique challenges that the Army faces. As with the ARL Open Campus initiative, the richness of data that could be collected through ARL facilities is an inexpensive way to collaborate, and if strategically planned, could support several different laboratories asking the same questions from different angles to more robustly inform the research in these multifactorial environments with emergent outcomes.

Human-autonomy teaming needs to include many team phases, including mutual training, planning, execution, and after-action reviews. "Training" is not used in the sense of procedures that are formally specified in another part of ARL, but rather highlights the need for most teams to develop shared understanding and expectations through shared experiences. Algorithms designed through ML based on a preconceived notion of team behavior may not lead to resilient and adaptive human-autonomy teams, so future research needs to consider how mutual adaptation of human to autonomy and vice versa leads to resilient and adaptive human-autonomy teams.

For the presentations of ARL's current human interest detection (HID) research efforts, context is needed. ARL needs to provide past work found in the literature, including previous work in attention focusing and ARL-supported work (especially in the Cognition and Ergonomics Collaborative Technology Alliance [CTA]). A framework is needed for binary target detection using the human interest measurements (probability of detection versus probability of false alarm and receiver operating characteristic [ROC]); this framework is likely to require adaptive decision fusion. A clear roadmap is needed, including potential dependency on related research from other programs, metrics for success, milestones, and timelines. Milestones could include three to five realistic test scenarios specifying how many subjects would be using the HID system in a field test, what tasks and targets will be looked at, what form factor and other wearability constraints would need to be met by the HID system, and what ROC or probability of detection/probability of false alarm performance points on the ROC curve would be achieved.

The cyber science group has made good progress in 2 years, including identifying areas where the Army has unique challenges. The cyber science group brings a unique skill set to the Army that could be left intact or allowed to grow to advance its science. The cyber science group possesses a skill set that could be attractive to other groups—for example, training or computer science. If that skill set were siphoned away into other groups within the Army, the human science that the group is advancing will suffer.

The kinesiology group is working in an important area of research. The research strives to ensure that physical agents such as exoskeletons are designed based on how humans need to move so that they can team well with the warfighter. For the future work that the group envisions, studying smart exoskeletons is an interesting path to pursue. However, this research effort needs to better understand the musculoskeletal "cost" of the technology. Supporting the physical performance of tasks that will continue to be allocated to human soldiers is an important contribution of this group. The group can play an important role in identifying those tasks at which human soldiers (with or without augmentation) will excel or be able to keep pace with robotic soldiers, and vice versa, as robotic technology advances.

Changes made in the personnel, organization, and structure of the HS core competency area have provided the tools and opportunities needed to make it a national laboratory in the area of cognitive science and robotics for individual human performance as well as for human teams and mixed teams of humans and robots. The funding directed to this group by the Army has enabled the researchers to build the next generation of high-technology research tools with which to study human performance in combat simulations both with and without robotic teammates.

MATERIALS AND MANUFACTURING SCIENCES

The research areas reviewed were optical science and photonics, electronics and optoelectronics, and energy science.

ARL's materials sciences span the spectrum of technology maturity and address Army applications, working from the state of the art to the art of the possible. The Army's vision for multi-domain operations (MDO) is that the Army of 2035 and beyond uses advanced technologies to achieve overmatch across a wide spectrum of domains and environments. The desired end state of the materials and manufacturing sciences core competency is to leverage the broad materials community to produce materials that enable the materiel to give soldiers unprecedented overmatch across the increasingly dynamic, complex, multi-domain battlefield of the future. Materials research efforts and expertise are spread throughout the ARL enterprise. As the ensemble of the materials discipline and capabilities, the area of materials and manufacturing sciences is one of ARL's primary core technical competencies. In the larger context, the mission of ARL, as the U.S. Army's corporate laboratory, is to provide innovative science, technology, and analyses to enable a full spectrum of operations.

Most of the projects presented are excellent and, in some cases, world-class, and have potential for pervasive impact on the Army. The scientific soundness and the use of fundamental sciences are outstanding. The project portfolio fits well with both global thrusts and the national agenda.

Collaborations throughout the optical sciences and photonics program were diverse and strong, to the extent that the research advances emanating from these partnerships demonstrates that "the whole is greater than the sum of the parts." That is, the time and effort invested by ARL researchers in developing these collaborations have resulted in a substantial return to the ARL research effort. The fundamental research conducted in the quantum information sciences group is especially impressive, and the demonstration of the first communications receiver based on Rydberg atoms is a major milestone of which all of ARL can be proud. The successful effort to store information in spin waves is also promising and a credit to this research team. The advanced solid-state lasers group continues to be one of the “crown jewels” for ARL by driving infrared laser technology with the recent achievement of lasing at 3 microns in new, low phonon energy hosts such as barium fluoride and yttrium lithium fluoride. The Sensor Protection scientific team is commended for the clever iridium chemistry that is being pursued to develop broadband reverse saturable absorption materials and the guided-mode resonance (GMR) filters. Among the impressive accomplishments of the integrated photonics research team is the dramatic improvement in the performance of optical frequency combs and the successful demonstration of electrically steerable phased arrays.

Overall, the research projects in the electronics and optoelectronics area were of high quality and comparable to other first-class research organizations. The projects evaluated were well thought out and motivated by Army needs—two examples are emerging materials being explored as a means to increase information and data assessment in the field and materials-driven antenna design that will address the Army’s expanding communications and size, weight, and power as well as cost (SWaP-C) needs. There was a good mix of exciting high-risk projects and those that are in support of Army near-term applications.

In the energy science area, clear linkages between ARL research programs and Army needs were, in most cases, well presented. Some strong and highly visible programs are internationally recognized and are likely to create opportunities to improve effectiveness of Army personnel in the field. In addition, there are less visible although essential efforts providing incremental advances specific to Army needs. The team working on aqueous lithium-ion battery (LIB) materials and systems is making exceptional advancements in the S&T of electrical energy storage with lithium-ion batteries. Aqueous electrolytes are nonflammable and thus dramatically safer than conventional electrolytes for military use. This ARL team has advanced the science of ultra-concentrated aqueous electrolytes that has enabled the use of high-voltage electrodes that previously were incompatible with aqueous systems. Work by the ARL team spans a broad range from computational modeling of interfacial chemistry to fabrication of cells of a size (approximately 5 Ah) suitable for field use. This is a wide range of activity for a small group that has deservedly garnered positive international recognition. Work on wireless energy transmission is also making excellent progress with capabilities for local wireless energy transmission (centimeters to meters) using electronic and acoustical waves, and is among the best in the world.

ARL’s work in preparing for the review was particularly noteworthy given the unknowns associated with this first effort at a virtual review. Overall, the researchers and the management are of high caliber and deserve credit.

PROPULSION SCIENCES

Programs assessed within the propulsion sciences core competency area were platform power, platform design and control, and intelligent maneuver.

The propulsion sciences research programs consist of internal and external research efforts. These research programs include ARL internal team efforts, partnerships with university investigators, and ARL-funded research in industry.

In general, propulsion sciences research is observed to be of high quality. The continued upward trajectory of developing well-posed research projects along with application of appropriate research tools and questions to investigate research challenges is noted. Advances in developing and applying basic dimensionless variables, simulation tools, and experimental laboratory facilities has expanded the opportunity space for ARL to produce disruptive and game-changing technologies. Greater success can be realized by increased intralaboratory research exchanges of goals, objectives, tools, methods and processes, and facilities—that is, monthly joint intralaboratory research seminars. Expanding interactions with university and industry partners can also accelerate success.

Development of disruptive technology is not uniform across the three program areas—platform power, platform design and control, and intelligent maneuver. Transition of S&T products to the commercial sector and the defense sector is nascent. Challenges in modeling complexity and advanced systems design including assessment remain.

Several research projects are considered exceptional accomplishments. The program on tribology and lubrication science is well formulated and aimed at understanding fundamental physics. This program has demonstrated commendable use of experimental facilities in fundamental research. Application of this capability to study the failure mechanisms for fuel pumps is an excellent application of fundamental capability in resolution of relevant problems—for example, operation using different fuels and under different atmospheric conditions.

A particular exemplar is the microstructure deep learning methodology applied to developing artificial intelligence/machine learning (AI/ML) approaches by fusing simulation and experimental data. The molecular dynamics modeling in both the computational design of shape memory polymer actuation and the tailorable and multifunctional dynamic polymer networks can provide data to implement AI methods. Dynamic polymer networks research is a unique combination of morphing, self-healing, and shape memory. The non-equilibrium molecular motor research is on the leading edge of bio-hybrid basic research and will help inform ARL to shape its future portfolio.

Research on tilt rotor development as an alternative to fixed quadcopter designs to control attitude and lift more independently from lateral motion can introduce significantly improved capability to aerial maneuvering. When added to a quadrotor small-unmanned aerial system (sUAS), the tilting and force capability showed promise over pure quadrotor variants, enabling a new level of control. This development offers capabilities beyond a standard unmanned aerial system (UAS), potentially leading to disruptive, game-changing functionalities. The interplay of model simulation and physical testing in this research was excellent.

In summary, workforce management continues to improve, as evidenced by recruitment, mentoring, and retention of new, outstanding researchers from top-tier academic universities. Presentations and posters for the review were all of high quality, reflecting continuous improvements of research content. Technical publications involving ARL researchers were also found to be of high quality. Overall, the ARL technical management team has been supportive to the researchers in recognizing and responding to opportunities for growth.

CROSSCUTTING RECOMMENDATIONS

Based on the 2019-2020 specific program review materials assessed in this report, the ARLTAB offers the following recommendations.

There is significant attention given to AI and ML in research programs across different portfolios at ARL. At present, the scope of these research efforts is rather narrowly focused on technical specialty areas. Fundamental research issues related to innovative ML techniques, AI implementation in resource-constrained environments, and trust and security of AI systems must still be addressed on a broader scale. It is also important to recognize that it is suboptimal to seek algorithmic advances in these areas without due consideration of hardware developments that are taking place in parallel. Given the potential of a disruptive impact of these technologies on Army operations, it is important to develop a comprehensive and integrative research plan in this emerging area. These technologies can have a transformational impact on key elements of future Army operations.

Crosscutting Recommendation 1: Activities in areas of artificial intelligence and machine learning are pervasive across Army Research Laboratory (ARL) research portfolios. ARL should emphasize the identification of a set of fundamental research questions that can provide

a long-term focus for research in this area. Rich and disparate data sets collected across multiple research domains at ARL (materials, weapon systems, human-machine interactions, for example) could provide the context against which answers to these research questions are pursued.

Software development has advanced at a tremendous pace over the past few years. Much of the reason for this rapid development is the increasingly common practice of employing open source software to build software platforms. Because of this rapid pace, it will be difficult for ARL to remain competitive within the software development space. ARL needs to be a member of GitHub[7] (if it is not already), with classified information being handled appropriately.

Crosscutting Recommendation 2: The Army Research Laboratory (ARL) should develop a mechanism for collaboration between ARL and industry on software development to ensure that it continues to track the state of the art. Specifically, ARL should use and develop software platforms in collaboration with open source software libraries that will enable ARL to keep up to date and to rapidly develop software.

High-quality research cannot be pursued in a vacuum. The probability of eventual success of ARL long-range research programs will be enhanced through cognizance of outside efforts and, where appropriate, establishing formal collaborations. Establishing contacts will require, at a minimum, attendance at professional meetings and conferences and possible travel to and from leading institutions.

Crosscutting Recommendation 3: To improve career prospects of early-career researchers and improve the overall quality of the research, the Army Research Laboratory (ARL) should further encourage and facilitate all members of the research team, including junior members, to make the scientific contacts and interactions necessary to adequately place their research in the context of the entire field.

[7] GitHub is a major open source group—see https://github.com/.

1

Introduction

This introductory chapter describes the biennial assessment process conducted by the National Academies of Sciences, Engineering, and Medicine's Army Research Laboratory Technical Assessment Board (ARLTAB). It then describes the preparation and organization of the report, the assessment criteria, and the approach taken during the report preparation.

THE BIENNIAL ASSESSMENT PROCESS

The ARLTAB is guided by the following statement of task:

> The National Academies of Sciences, Engineering, and Medicine will appoint a committee to be named the Army Research Laboratory Technical Assessment Board (ARLTAB), to be overseen by the Laboratory Assessments Board (LAB), to continue the function of providing assessments of the scientific and technical quality of the research at the Army Research Laboratory (ARL). The committee will develop a series of reports that summarize the ARLTAB's findings, conclusions, and recommendations related to the quality of ARL's research programs.
>
> Every two years, the committee will assess six portions of the ARL technical program (three in year 1, three in year 2). To conduct its assessments the ARLTAB will be assisted by up to six separately appointed panels. The assessment completed in Year 1 will be released as an interim assessment report, which will be combined with the second year's assessment as a final biennial report.
>
> The committee will also review the extramural basic research programs at the Army Research Office (ARO), a subdivision of the ARL. Each year the ARLTAB will be supported by an additional panel that will focus on selected ARO programs, and the ARLTAB will annually provide a separate assessment report.
>
> While the primary role of the ARLTAB is to provide peer assessment, it may also offer advice on related matters when requested by the ARL Director.

The charge of the ARLTAB is to provide biennial assessments of the scientific and technical quality of the Army Research Laboratory (ARL). These assessments include the development of findings and recommendations related to the quality of ARL's research, development, and analysis programs. The ARLTAB is charged to review the work in ARL's research core competencies: network and information sciences, computational sciences, human sciences, materials and manufacturing sciences, propulsion sciences, ballistic sciences, and protection sciences,[1] but not the work of the Army Research Office (ARO), a key element of the ARL organization that manages and supports basic research. However, all ARLTAB panels receive reports of how the research and development (R&D) activities of ARO and ARL

[1] The ARLTAB will assess the ballistic sciences and protection sciences research core competencies in 2021 because the planned in-person 2020 meeting of the panel could not take place owing to COVID-19. Its meeting could not be conducted virtually because the research in ballistic sciences and protection sciences areas involved controlled unclassified information and classified information.

are coordinated. The ARO programs are assessed by different panels that are also overseen by the ARLTAB.

In addition, at the discretion of the ARL director, the ARLTAB reviews selected portions of the work conducted by the Collaborative Technology Alliances (CTAs) and Cooperative Research Alliances (CRAs). Although the ARLTAB's primary role is to provide peer assessment, it may also offer advice on related matters when requested to do so by the ARL director; such advice focuses on technical rather than programmatic considerations. To conduct its assessments, the ARLTAB is assisted by five National Academies panels, each of which focuses on one or more of ARL's research core competencies. The ARLTAB's assessments are commissioned by ARL itself rather than by one of its parent organizations.

For this assessment, the ARLTAB consisted of 10 leading scientists and engineers whose collective experience spans the main topics within ARL's scope. Five panels, each of which focuses on one or more of ARL's research core competencies, report to the ARLTAB. Nine of the ARLTAB members serve as chairs or co-chairs of these panels or the panels assessing the ARO programs. The panels range in size from 13 to 19 members, whose expertise is carefully matched to the technical fields covered by the areas that they review. Selected members of each panel attend each annual review. In total, 68 members participated in the reviews that led to this report. All panel and ARLTAB members participate without compensation.

The National Academies appointed the ARLTAB and panel members with an eye to assembling a slate of experts without conflicts of interest and with balanced perspectives. The experts include current and former executives and research staff from industrial R&D laboratories, leading academic researchers, and staff from the Department of Energy (DOE) national laboratories and federally funded R&D centers. Seventeen are members of the National Academy of Engineering, and four are members of the National Academy of Sciences. A number have been leaders in relevant professional societies. The ARLTAB and its panels are supported by National Academies staff, who interact with ARL on a continuing basis to ensure that the ARLTAB and the panels receive the information they need to carry out their assessments. The ARLTAB and panel members serve for finite terms, generally 4 to 6 years, so that viewpoints are regularly refreshed and the expertise of the ARLTAB and panel members continues to match ARL's activities. Biographical information on ARLTAB members appears in Appendix B.

In 2019 and 2020, four panels reviewed the following research core competencies of ARL:

- Human sciences,
- Network and information sciences,
- Computational sciences,
- Materials and manufacturing sciences, and
- Propulsion sciences.

This biennial report summarizes the findings of the ARLTAB from the reviews conducted by the panels in 2019 and 2020 and subsumes the 2019-2020 interim report.[2]

PREPARATION AND ORGANIZATION OF THIS REPORT

The current report is the eleventh biennial report of the ARLTAB. Its first biennial report was issued in 2000; annual reviews were issued in 1996, 1997, 1998, 2013, 2015, 2017, and 2019. As with the earlier reviews, this report contains the ARLTAB's judgments about the quality of ARL's work. (Chapters 2

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[2] National Academies of Sciences, Engineering, and Medicine, 2020, *2019-2020 Assessment of the Army Research Laboratory: Interim Report*, The National Academies Press, Washington, D.C.

through 6 focus on the research core competencies areas, and Chapter 7 provides a discussion of crosscutting issues across all of ARL.) The rest of this chapter explains the rich set of interactions that supports those judgments.

The amount of information that is funneled to the ARLTAB, including the evaluations by the recognized experts who make up the ARLTAB's panels, provides a solid foundation for a thorough peer review. This review is based on a large amount of information received from ARL and on interactions between ARL staff and the ARLTAB and its panels.

To further improve the overall process of preparing for review, the ARLTAB requests that information listing the full spectrum of projects and programs in each ARL campaign be provided and an interrelated mapping of projects across all campaigns be provided as a read-ahead before the panel meeting. The process of preparing such a snapshot in time would be of utility in focusing future reviews as well as to ARL in developing cohesiveness and priorities.

Most of the information exchange occurs during the annual meetings convened by the respective panels at the appropriate ARL sites. Both in formal interactions during technical presentations and in less formal interactions during poster sessions and during joint lunch or dinner sessions,[3] ARL evinces a very healthy level of information exchange and acceptance of external comments. The assessment panels and the ARLTAB engaged in many constructive interactions with ARL staff during their annual site visits in 2019 and the virtual meetings in 2020. In addition, useful collegial exchanges took place between panel members and individual ARL investigators during the meetings as ARL staff members sought clarification about panel comments or questions and drew on panel members' contacts and sources of information.

Each panel's review meeting lasted about 2.5 days, during which time the panel members received a combination of overview briefings by ARL management and technical briefings by ARL staff. Prior to the meetings, panels received extensive materials for review, including selected staff publications.

The overview briefings brought the panels up to date on the broad scope of ARL's scientific and technical work. This context-building step was needed because the panels are purposely composed of people who, while experts in the technical fields covered by ARL's research core competencies that they reviewed, were not engaged in collaborative work with ARL. Technical briefings for the panels focused on R&D goals, strategies, methodologies, and results of selected projects at the laboratory. Briefings were targeted at coverage of a representative sample of each of ARL's research core competencies. Briefings included poster sessions that allowed direct interaction among the panelists and staff of projects that were not covered in the briefings.[4]

Ample time during both the overview and the technical briefings was devoted to discussion, which enabled panel members to pose questions and ARL staff to provide additional technical and contextual information to clarify panel members' understanding. The panels also devoted sufficient time to closed-session deliberations, during which they developed findings and identified important questions or gaps in panel understanding. Those questions or gaps were discussed during follow-up sessions with ARL staff so that the panel was confident of the accuracy and completeness of its assessments. Panel members continued to refine their findings, conclusions, and recommendations during written exchanges and teleconferences among themselves after the meetings.

In addition to the insights that they gained from the panel meetings, ARLTAB members received exposure to ARL and its staff at ARLTAB meetings each winter. The 2019 and 2020 ARLTAB meetings refined elements of the assessment process focused on ARL's research core competencies, including read-ahead materials, review agendas, and expertise required within the panels.

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[3] As noted earlier, the 2020 panel meetings on materials and manufacturing sciences and propulsion sciences were held virtually and did not benefit from such joint lunch or dinner sessions.

[4] Agendas of the panel meetings can be found at the National Academies of Sciences, Engineering, and Medicine website at http://www8.nationalacademies.org/cp/ for each respective panel.

ASSESSMENT CRITERIA

During the assessment, the ARLTAB and its panels considered the following questions posed by the ARL director:

- Is the scientific quality of the research of comparable technical quality to that executed in leading federal, university, and industrial laboratories both nationally and internationally?
- Does the research program reflect a broad understanding of the underlying science and research conducted elsewhere?
- Does the research employ the appropriate laboratory equipment and numerical models?
- Are the qualifications of the research team compatible with the research challenge?
- Are the facilities and laboratory equipment state of the art?
- Are programs crafted to employ the appropriate mix of theory, computation, and experimentation?

To assist ARL in addressing promising technical approaches, the ARLTAB also considered the following questions:

- Are there especially promising projects that, with improved direction or resources, could produce outstanding results that can be transitioned ultimately to the field?
- Are there promising outside-the-box concepts that could be pursued but are not currently in the ARL portfolio?

Within the general framework described earlier, the ARLTAB also developed, and the panels selectively applied, detailed assessment criteria organized in the following four categories (Appendix C presents the complete set of assessment criteria):

1. *Project goals and plans.* Criteria in this category relate to the extent to which projects address ARL strategic technical goals and are planned to effectively achieve the stated objectives.
2. *Methodology and approach.* Criteria in this category address the appropriateness of the hypotheses that drive the research, of the tools and methods applied to the collection and analysis of data, and of the judgments about future directions of the research.
3. *Capabilities and resources.* Criteria in this category relate to whether current and projected equipment, facilities, and human resources are appropriate to achieve success of the projects.
4. *Scientific community.* Criteria in this category relate to cognizance of and contributions to the scientific and technical community whose activities are relevant to the work performed at ARL.

APPROACH TAKEN DURING REPORT PREPARATION

This report represents the ARLTAB's consensus findings and recommendations, developed through deliberations, which included consideration of the notes prepared by the panel members summarizing their assessments. The ARLTAB's aim with this report is to provide guidance to the ARL director that will help ARL sustain its process of continuous improvement. To that end, the ARLTAB examined its extensive and detailed notes from the many ARLTAB panel and individual interactions with ARL during 2019-2020. From those notes, it distilled a shorter list of the main trends, opportunities, and challenges that merit attention at the level of the ARL director and the management team. The ARLTAB used that list as the basis for this report. Specific ARL projects are used to illustrate these points in the following chapters when it is helpful to do so, but the ARLTAB did not aim to present the director with a detailed account of interactions with bench scientists. The draft of this report was subsequently honed and reviewed according to the National Academies' procedures before being released.

The ARLTAB applied a largely qualitative rather than quantitative approach to the assessment. The approach of the ARLTAB and its panels relied on the experience, technical knowledge, and expertise of its members, whose backgrounds were carefully matched to the core technical competency areas in which ARL activities are conducted. The ARLTAB and its panels reviewed selected examples of the scientific and technological research performed by ARL; it was not possible to review all ARL programs and projects exhaustively. Given the necessarily non-exhaustive nature of the review process, the omission of mention of any particular program or project should not be interpreted as a negative reflection on the omitted program or project.

The ARLTAB's goal was to identify and report salient examples of accomplishments and opportunities for further improvement with respect to the technical merit of ARL work and specific elements of ARL's resource infrastructure that are intended to support the technical work. Collectively, these highlighted examples for each ARL research core competency are intended to portray an overall impression of the laboratory while preserving useful mention of suggestions specific to projects and programs that the ARLTAB considered to be of special note within the set of those examined.

Along these lines, in applying the first assessment criteria ("Is the scientific quality of the research of comparable technical quality to that executed in leading federal, university, and industrial laboratories both nationally and internationally?"), the ARLTAB uniformly characterize ARL's work as high, moderate, or low quality compared to that executed in leading federal, university, and industrial laboratories both nationally and internationally.

REPORT CONTENT

This chapter has addressed the biennial assessment process used by the ARLTAB and its five panels. Chapters 2 through 6 provide detailed assessments of the research core competencies reviewed during 2019-2020. Chapter 7 presents findings common across multiple research core competencies. The appendixes provide ARL's research core competencies and their mapping to the technical areas reviewed in 2019 and 2020, biographical information on the ARLTAB members, the assessment criteria used by ARLTAB and its panels, and a list of acronyms found in this report.

2

Network and Information Sciences

The Panel on Information Science at the Army Research Laboratory (ARL) conducted its review of selected research and development (R&D) projects of the ARL network and information sciences research core competency at Adelphi, Maryland, on June 18-20, 2019. The research areas reviewed were information sciences and networks and cyber.

ARL research in information sciences seeks to develop new technologies that allow for information acquisition, analysis, reasoning and decision making, and assurance of information and knowledge. This research effort targets technological developments and enhancements that allow for efficient management of information in a dense data environment, extracting knowledge to deploy distributed intelligent systems, and to build effective systems for multi-domain operations (MDO) that will define the battlespace of the future. Technologies resulting from these efforts will have a direct impact on future Army capabilities in C4ISR,[1] networks, intelligent systems, and cybersecurity.

The research projects under the banner of information sciences (IS) had a significant emphasis on artificial intelligence (AI) and machine learning (ML) as applied to diverse areas of Army relevance. Application areas included image understanding, automated language processing, augmented and virtual reality (AR/VR), and learning for control. There was a focus on MDO, and research projects were both foundational and disruptive, while maintaining Army relevance. There is a broad embrace of the transformative potential of AI and ML, especially in the context of how groups of people and autonomous systems can seamlessly collaborate, how technology can further aid with time-sensitive decision making in the presence of massive and diverse sources of information, and how virtual and augmented reality can be integrated in Army operations.

Research in the area of networks and cyber includes projects that fall into the general area of human-robot/machine interactions, with the two principal threads being scene narrative generation for humans by robots and robot learning from human demonstrations. This body of work is ambitious and has the potential to disrupt the way human-robot interactions are considered for future battlefields. Another important research methodology, especially for security issues, is to study systems that have both defense and offense techniques. The “adversarial learning” project is a great example of researchers working on new research areas, with the goal of leveraging what they learn to build better defenses. ML rightly pervades multiple research topics in this thrust.

[1] C4ISR stands for command, control, communications, computers, intelligence, surveillance, and reconnaissance.

INFORMATION SCIENCES

Accomplishments and Advancements

The research portfolio in information sciences addresses the challenge of overcoming the computational and network resource constraints to develop approaches that facilitate and enhance human-machine interaction, and to build human-like capabilities in autonomous systems to identify saliency in visual images. The research portfolio was a mix of basic and applied research, and some of the projects show clear potential for transition into Army applications and products. The researchers are to be complimented for a range of projects that represent a wide swath of Army-relevant IS topics, with particular emphasis on tactical perception and learning, and humans and robots.

Success in tactical environments requires the successful deployment and use of edge devices. Here, edge devices refer to devices that employ a distributed computing paradigm that brings computation and data storage closer to the location where it is needed, to improve response times and save bandwidth. The processing and analysis of data from such devices requires significant computational resources that need to be either off-loaded or accessed in a distributed computing network. Both approaches represent vulnerabilities to attack. ARL seeks a secure adaptive computing framework for the tactical environment and is exploring both traditional security approaches and AI-enabled systems that focus on both efficiency and security.

The ARL focus on human-machine interactions stems from an understanding that current "autonomous" systems require continual human involvement. The tactical environment is unstructured and continually changing. As such, it is difficult to provide reliable a priori information about the environment in which the autonomous system will operate. An important focus of ARL research, therefore, is on the human-in-the-loop ML techniques to help develop autonomous agents and systems.

ARL research is also examining techniques for detecting and prioritizing objects and locations within a visible image to enable better autonomous maneuver and operations within a multidomain environment. Toward this end, research is being directed to extend models of visual salience from standard dynamic range (SDR) to high dynamic range (HDR) environments.[2] The focus is on developing computational models to predict behavioral and neurophysiological effects of HDR luminance.

The research review consisted of a number of presentations on topics such as learning from imitation, risk-aware learning, HDR saliency, and reinforcement learning for adaptable agents. There were also a number of poster presentations in these subject areas, including research on imitation from observation, semantic-based autonomous navigation, learned control policy, and information agents for value assessment. Posters also presented research on saliency in HDR environments, in camouflage, and for moving objects and observers. Research in multitask learning as applied to accent language learning and in morphologically complex language processing was also presented in a poster.

Augmented Reality for Human-Robot Teaming in Field Environments

This project addresses the problem of collaboration between humans and a mobile robot in exploring an unknown environment. Through bidirectional communication, the human and robot know each other's locations and plans, and can jointly create a map of the shared environment (without global positioning

[2] SDR displays typically use 8 bits of color depth. This limits the contrast ratio for display to about 1,200 to 1. HDR displays typically require a minimum of 10 bits of color depth. In this scheme, it is fairly easy to obtain contrast ratios well over 200,000 to 1. In HDR displays, the backlight is often divided into smaller zones and controlled individually. Matching the brightness of these zones to the overlaid pixel data extends the contrast range for the user.

systems [GPS]). Augmented reality allows the human to easily "see" parts of the environment that have already been explored, and to make recommendations on where to explore next. The approach is being validated through experiments conducted at the Military Operations in Urban Terrain (MOUT) Laboratory. The project involves multiple university partners and collaborators. Overall, this is an important area of research for the Army.

Time-Delayed Neural Networks for Acoustic Models Using Multitask Learning as a Domain Adaptation

Global reach and engagement are at the core of Army operations. There is a clear need for improved speech-to-speech translation technologies, especially in languages for which there is limited availability of training data. Research in this project is focused on developing a deep neural network-based multitask learning approach to leverage existing large training sets from another language. Through the use of shared intermediate representation to simultaneously learn speech-to-speech models for both languages, the approach provides for improved accuracy of the models learned. This project represents a prime example of leveraging a state-of-the-art approach to solve a critical need and of significantly enhancing Army operations.

Salience of Highly Informative but Nonobvious Regions of Interest

Saliency models are designed to focus on obvious features in an image. This research project is directed at developing models that are trained to identify subtle characteristics in an image and to prioritize obvious and nonobvious regions. The research seeks to incorporate semantic information and the embedded relational clues in the model training process. This project is just at the inception stage. The overall aim of the project is important and represents a potentially niche area of Army interest.

Modeling Visual Salience in High Dynamic Range Environments

Visual salience is an important characteristic that is central to the study of visual search. It is used to identify and prioritize images that define a visual scene. Many extant measures of visual saliency are adequate for images with 8-bit SDR. However, these measures need be readdressed in HDR images, where existing theories of luminance perception are less applicable. The project focuses on the development of computational models of visual salience that address shortcomings of standard saliency models. The focus of the work is on modeling interactions of complex features to improve the predictive capability of computational models. In particular, models drawn from neurophysiological studies on HDR are considered promising in the work. Additional model development, training, and testing are required to assess the impact of the work.

Modeling the Salience of Partially Obscured and Camouflaged Objects Under Relative Motion

The research is focused on developing and training spatiotemporal saliency models that improve detection of partially obscured objects. The concept of motion parallax is deployed for the detection of occluded and camouflaged objects, using a spatiotemporal saliency model. Such an approach can contribute to improved situational understanding. Virtual reality simulations were used to generate video data with motion parallax to train deep learning neural networks that will be tested against spatiotemporal test data. The project is a multiyear effort and is at a preliminary stage. While substantial results are yet to be obtained, preliminary findings indicate that including motion parallax in detection improves the current spatiotemporal saliency models. Additional work is required to assess how camera motion affects obscured object detection.

Learning Control Policies for Perception in Large Environments

This project is directed at addressing challenges related to developing situation awareness for diverse Army scenarios. The focus of the work is to automatically learn the camera pan, tilt, and zoom parameters for different contexts and scenarios. A deep reinforcement learning-based approach is pursued, and some depth estimation results have been obtained. However, this work is still at a preliminary stage and significantly more tasks are planned to overcome multiple challenges that the project expects to address.

Semantic-Based Autonomous Navigation

The work in this project is motivated by the need to adapt a vehicle's autonomous driving software to operate effectively in new settings. In an off-line mode, an inverse optimal control approach is used to develop a reward function that visualizes feature maps and trajectory exemplars. This reward function is then used in an online mode where features of the operating environment are presented to develop the navigation path. Experimental testing was done at a MOUT site. The project is an excellent example of technology translation from basic research developed through a Collaborative Technology Alliance (CTA) to ARL. The work is clearly significant for Army applications, and related publications are strong.

Information Agent for Assessing Value

This research project work explores modeling of information prioritization that subject matter experts make. The impact of the work can be potentially significant because it can both augment and amplify the human effort that underlies this task. Although some interesting preliminary results have been generated, it would be important to clearly enunciate the rationale for the chosen approach, what competing strategies are possible, and whether the proposed approach performs better than existing solutions to this problem.

Neural Network Models for Low-Resource and Morphologically Complex Language Processing

This project is designed to improve the information extraction capabilities for morphologically complex languages such as Russian and Ukrainian by developing deep neural network-based morphological classifiers for such languages. Neural approaches have not always proven effective in low-data scenarios, and segmental recurrent neural networks and sequence-to-sequence neural networks were deployed for morphological analysis and generation, respectively, with 90-92 percent accuracy. Although these results are promising, it is not obvious how significant the improvements are over existing approaches and why commercial (translation or morphological analysis) solutions are not sufficient.

Imitation from Observation

This research focuses on human-in-the-loop ML techniques to develop autonomous AI agents for Army applications. The work represents an extremely productive and substantive collaboration between researchers at ARL and at the University of Texas, Austin, focused on building autonomous systems through reinforcement learning from human demonstrations of desired behaviors. The research examines strategies to extend behavior cloning and inverse reinforcement learning to the information from observation environment. The work is of high scientific quality, addressing emerging questions in ML and AI—such as how to learn when you do not have large quantities of data. It is also being published in top-tier publications venues for work in this area.

Challenges and Opportunities

The research projects were focused on important areas, and researchers were generally able to articulate Army relevance and needs. The overall quality of the research was high, but not uniformly so. In most cases, the posters and presentations provided sufficient details about assumptions made and the major steps followed in the conduct of the research. This was not always the case, and research quality, impact, and understanding would be improved by additional attention to these descriptions in the posters and oral presentations. Some of the presentations did not recognize connections to existing research outside ARL, and in some cases, it was not clear why existing techniques were considered to be inadequate to address the problem. In a few cases, the research problem statements could have been more ambitious.

The research related to imitation from observation was outstanding and potentially disruptive. The work on semantic-based autonomous navigation was a good example of application of technology invented in a CTA that led to a research project at ARL. The project with the goal to learn control policies is clearly highly relevant but can benefit from a widening of scope to consider alternative approaches. Additionally, some interaction with researchers working in saliency may have beneficial impact.

The virtual reality demonstration illustrated a technology of potentially high impact. The project on augmented reality for human-robot teaming represents a promising area for ARL researchers; partnering with the virtual reality research team may offer new avenues for exploration in this context. In particular, research on human-robot teaming could benefit from collaboration with the ongoing work on immersive virtual reality. Doing so would allow for the exploration of immersive approaches to presenting multimodal data to humans.

The research on natural language processing was promising, and work related to application of multitask learning to small-corpus accented speech recognition is clearly an important area for research. The analysis of morphologically complex languages was creative and may fill a need—competing approaches could be considered in this context.

The ongoing work related to information agents for assessing value would benefit from asking more ambitious questions in richer problems, and to bring in other ML methods. Significant effort is directed at analyzing saliency in video; this work is both important and impactful. This work could benefit from consideration of related approaches in the literature, crystallization of goals, and clear plans to achieve them.

NETWORKS AND CYBER

Accomplishments and Advancements

The research portfolio in the area of networks and cyber seeks greater understanding of the general area of diverse communications modalities, and human-robot/machine interactions. It is also focused on a study of adversarial systems as they relate to cybersecurity. ML and AI are central to many of the ongoing research projects.

The research reviewed was high quality and comparable to research conducted at other federal laboratories and educational institutions. For the majority of the research projects, it was clear that the scope of the research was informed by the needs and unique challenges of the Army. Research efforts were adequately referenced and, in many instances, results from ongoing research were benchmarked against those available in the literature. The research findings are being published in high-quality venues.

In the area of diverse communication modalities, the focus is on developing mobile networking with favorable propagation characteristics in obstructed environments, avoiding detection, and minimizing risk of signal interception, and in general, enhancing network capacity and capabilities. A significant focus is on using mathematical constructs of geometry and topology to explain network characteristics.

In the context of cybersecurity, an important thrust is the security of Army vehicle platforms. Military vehicles contain multiple embedded networked systems that also seek information from external networks for successful operations. In this context, ARL is pursuing research to develop an active defense network for electronically controlled automated vehicle systems. Research in game theory, adversarial ML, and human-machine teaming is being considered in this context.

Research is also directed at developing strategies to ensure robust operation of a "network of things" that have the propensity to fail, exhibit degraded performance, or may be compromised in operation. Approaches based on blockchain technology are being explored in this context. Principles of "fog computing" are also being adopted to address key problem areas.

Some research projects were considered to be exceptionally strong and offer significant potential to contribute to U.S. Army capabilities. Research related to active defense and dynamic watermarking for cyber defense of vehicles and other cyber-physical systems was one such effort where commercial vendors are unlikely to provide solutions. This significant cyber vulnerability represents a pervasive problem in most major Army vehicles.

Another noteworthy project was in the area of narrative generation as it relates to human-robot interaction. The focus of this effort was in developing an understanding and explanation of visual scenery by extracting information and adding captions to video stills that describes relevant scene information and ultimately what transpired. This result alone, if successful, could provide the warfighter a significant workload reduction in processing full motion video or still frame imagery. While not the focus of the ongoing work, this research could potentially also save communications bandwidth by the transmittal of the textual descriptions of the scenes instead of the full motion video.

Low-Power, Low-Frequency Mobile Networking

The goals and objectives of the project were to understand diverse communications modalities for more robust and covert operations, understand physical layer challenges and limitations, improve low probability of detection and low probability of intercept, and exploit autonomous agents that enhance networking capabilities and control radio radiation signatures.

High-frequency communications have favorable propagation characteristics in obstructive terrain but also require physically large antennas. The research leveraged previous very high frequency (VHF) antenna design work on three-dimensional (3D) structural antennas that were cited as having an electrical length of 1/50 lambda, which is physically quite small. The non-Foster design technique used enabled an antenna at VHF to exhibit outstanding electrical length of less than 0.1 meter; the antenna does, however, suffer significantly in transmission efficiency, which is predicted by the fundamental limit. The approach taken by the researcher was to further expand the capabilities of the passive antenna by adding active and passive inductive loading to the antenna, resulting in an increased transmission efficiency. The simulated active proposed design appears to offer larger bandwidth support and a higher transmission efficiency over the passive design.

Multiuser Networking with Improved Low Probability of Detection and Low Probability of Intercept

This research seeks to develop an understanding of the propagation channel by analyzing indoor propagation in an office-type environment at VHF frequencies. An environment of concrete walls with metallic reinforcement at a center frequency of 40 MHz and a bandwidth of 4 MHz was considered in the work. The antennas were composed of dipoles, and the environment was simulated using the industry standard finite-difference time-domain approach for electromagnetic simulation and prediction. The research also included a waveform delay-tolerant chip encoding method. The results showed that encoding can tolerate delays of several chips in multipath propagation without severe deterioration in waveform detection performance. The simulation also demonstrated that two users could operate in the channel simultaneously with comparably small chip delays.

Adversarial Machine Learning of Cyber Defense

This research project is directed at studying adversarial ML in the context of network security. The canonical problems center on adversaries injecting data into the network to confuse friendly classifiers. Similar problems have been studied extensively with images and videos, usually for deep learning and with generative adversarial networks. In the network case of interest to the Army, much less data is available and most classifiers in use are support-vector machines rather than neural networks. Hence, the focus is on support-vector machines. This project leverages ARL's unique network emulation and data sets and focuses on techniques for constructing traffic that evades attack detection. Playing the adversary, the researchers were able to increase the false negative rate from 0 percent to 24 percent. Moving forward, the challenge will be to move to other kinds of classifiers (e.g., deep neural networks). This work was done in collaboration with university researchers.

Active Defense Systems for Vehicle Platforms Dynamic Watermarking

This research focuses on a novel method for detecting cyberattacks on vehicles and other cyber-physical systems. The approach is to inject a minor but known noise signal into control data in a way that allows detection of the output effects (the "watermark"). If control or sensor data is later hacked, the expectation is that the watermark will no longer be detectable. This project is closely related to a larger effort in active defense, and is being conducted in collaboration with University of Texas, Austin, and Texas A&M. The researchers have validated the ideas in the laboratory and are working toward validation in real vehicles to ensure that the injected signal does not adversely affect the operation of the vehicle. The work has been published in a leading journal and additional publication is being pursued in addition to filing of patent disclosures. The work is both novel and highly relevant to Army needs; it is unlikely that these kinds of attacks will be addressed by commercial automotive manufacturers. The validation of the approach with real vehicles lends additional credence to the results.

Fog Computing and the Tactical Distributed Ledger

These research projects represent two approaches to ensuring robust operation of a "network of things" such as cameras, directories, storage nodes, and so on, where the individual things fail, are replaced, or have degraded performance. In particular, the focus is on cases where if a particular resource that fails has generated data and done partial computation, a replacement would be able to continue from where its predecessor left off. Additionally, the research seeks approaches wherein new nodes would be able to join the network and to ensure that only authorized nodes be able to join.

The tactical distributed ledger project leverages a combination of existing blockchain technology and other techniques to solve many of these problems. A traditional public key/certificate approach is used for authorization. The tactical distributed ledger stores state in multiple locations, and “smart contract” technology allows resources to advertise their application programming interfaces and permits nodes that require services from resources to be able to advertise their needs.

The fog computing project is at an early stage of framing the overall concept. There are interesting questions that need to be addressed that pertain to efficient management of computing resources. For instance, is it better to expend network bandwidth to ensure that the state is captured reliably at all times (needed only if the resource dies), or to have the application start computation over and deal with partial data? Are certain tasks better attuned to one approach? Can the approach be flexible so that when certain resources become scarce, the approach adapts? The fog can even have connectivity to a cloud, so that select portions of the data can be more robustly stored, and reached if necessary, with greater latency, from the cloud.

Geometric and Topological Structures in Complex Networks

This project focuses on the structure of graphs and the role that geometry and topology can play in explaining key features in networks, such as predicting small group evolution or finding sparse covers. Real network data is used to determine the efficacy of techniques from geometry, such as curvature, or techniques from topology, such as homology, to identify features that are invariant under reduction. One motivating example is determining whether there are coverage holes owing to GPS-denied network of devices. The project would benefit from a careful consideration of the network environments of the future Army. If this work is generally applicable to all networks, then researchers in academia and industry would be pursuing similar approaches; such connections to the literature were not made clear. A number of papers have appeared in conferences devoted to this area, and the work fits squarely within the basic research mission of ARL.

Narrative Generation for Human-Robot Interactions

This research is directed at developing approaches by which a robot can determine what happened in a block of time that is represented by sequence of images, and based on that understanding, generate a narrative for a human teammate. The problem is distinguished from related work available in the literature by constraints that are particularly important to the Army, such as low-quality, noncanonical imagery. This project integrates other lines of work at ARL such as the development of ontologies for image recognition. The approach uses crowdsourcing to generate general models of how humans handle narrative generation.

Uncertainty-Aware Artificial Intelligence and Machine Learning

The goal of this project is to develop methods to express both epistemic and aleatory uncertainty[3] in ML and AI. Most AI approaches focus on characterizing aleatory uncertainty but do not perform well

[3] Aleatory variability is the natural randomness in a process. For discrete variables, the randomness is parameterized by the probability of each possible value. For continuous variables, the randomness is parameterized by the probability density function. Epistemic uncertainty is the scientific uncertainty in the model of the process. It is the result of limited data and knowledge. The epistemic uncertainty is characterized by alternative models.

with limited training data. The strategy used is to indicate the degree to which classification results depend on prior versus observed data. The approach, which includes replacing the soft-maximum probabilities usually produced by deep neural nets with parameters for probability distributions, appears to be novel and far-reaching. Initial work has been published in top-tier conferences and journals. The work is being pursued in collaboration with researchers at three universities.

Challenges and Opportunities

In most of the projects, it was clear how the scope of the research was informed by the needs and unique challenges of the Army. The researchers were able to express a clear understanding of the degree to which their work overlaps research performed in academia and other research laboratories.

In relation to the work on fog computing and the tactical distributed ledger, there are continuing challenges in the blockchain approach that could be explored in future research. For example, there are challenges with network partitioning and healing or merging two blockchains. Other challenges include storing the entire blockchain and replication of computation across each node. The researchers clearly understand these problems. It would be important to cleanly separate requirements of the fog application from the features provided by blockchains so that different substrates can be tried.

Several research projects fall into the general area of human-robot/machine interactions, with the two principal threads: scene narrative generation for humans by robots and robot learning from human demonstrations. This body of work is ambitious and has the potential to disrupt the way human-robot interactions are considered for future battlefields. The portfolio of research would benefit from closer interaction between the two principal threads. For instance, there is the potential to use inverse reinforcement learning methods to aid in making narrative generation more personal and contextual. The work would also benefit from investigation into the sensitivity of human narrative to Army scenarios.

Machine learning rightly pervades multiple research topics. The applications of this technology to various research interests may or may not yield favorable results, and healthy skepticism by researchers would be prudent.

OVERALL QUALITY OF THE WORK

Information Sciences

The research work in IS was assessed to be generally of high scientific quality, but not uniformly so. The research portfolio represents an appropriate balance of theoretical and experimental work, and many of the more mature programs—but not all—show a transition into practice or use by other areas.

In most cases, the research projects reflected a good understanding of the problems being considered, an appropriate statement of the problem being pursued, a good knowledge of the appropriate methodologies to address the problem, and acquaintance with the state of the art and the relevant research pursued elsewhere.

In many cases, the researchers are able to articulate Army relevance and identify research challenges that are unique to the Army's operational needs. The researchers are well-qualified to carry out the research problems that they are pursuing and follow rigorous research methodologies and practices. Many of the projects have already resulted in publications in highly visible journals and selective conferences. The computation facilities and instrumentation required are adequate to the needs of the researchers.

Networks and Cyber

The overall scientific quality of the research was high, and comparable to research conducted at top research universities and government and industry laboratories. Researchers were very familiar with the underlying science and relevant leading research published and performed elsewhere. In many cases, there are active communications or collaborations with researchers outside ARL, many at the forefront of their respective fields. In all cases, the researchers were aware of the potential challenges, risks, and risk mitigations associated with their projects. In most cases, the researchers were able to incorporate these challenges, risks, and risk mitigations into their research.

There is an appropriate balance of theory, computational work, and physical experimentation to inform and investigate multiple areas of research. The facilities and supporting infrastructure are well-suited for collaborative work. There is a good mix of well-trained research personnel who also collaborate with researchers in a broad range of academic and industrial partners in addition to working with the ARL South and ARL West regional sites. The research staff in this area have received outstanding recognitions and awards for their research and technical contributions.

RECOMMENDATIONS

Information Sciences

The research related to imitation was found to be particularly noteworthy, drawing upon the notion that autonomous agents can learn via imitation of human “teachers,” of which the Army has many. The two approaches (reinforcement learning and inverse reinforcement learning) are not new, but the research here addresses cutting edge technology, and the results are potentially disruptive. It represents a new way to automate. The demonstration of the virtual reality was also viewed positively, with the recognition that notably high-quality experience could be disruptive for situational awareness related to Army operations. ARL could leverage the platform as a test-bed for ideas such as integration of satellite perspective, multiperson teaming, and human/agent teaming, and so on.

Most of the other projects, while not deemed as disruptive (a high bar), represent good research efforts and also provide ARL with the opportunity to develop human capital with expertise in ML and AI. Some projects would benefit from more ambitious goals, such as not only matching human levels of performance but perhaps surpassing it. Example topical areas where this may apply include autonomous navigation and visual saliency.

Much of the basic research in IS stems from the essential research area (ERA) projects or from one of the Collaborative Technology/Research Alliances (CTAs and CRAs). It is noted that many strong projects involve personnel embedded outside the ARL campus and that the initiative and coordination required to support such collaboration is to be lauded. The quality of the early-career ARL researchers in the IS area is high. The deployment of co-ops and interns, as well the Open Campus Initiative, has led to the recruitment of a strong cadre of emerging researchers.

Because this review was restricted to a subset of ongoing research projects, it was difficult to identify potential gaps in the portfolio. The coverage of AI appeared to be somewhat uneven, perhaps an outcome of the process of selection for presentation at the review. A stronger focus in areas like adversarial learning, integration of simulation in ML, and security related to ML would have provided a better understanding of the scope of ongoing work. As an example, simulation is emerging as a prominent element in training AI/ML systems, where physics-based simulation engines provide data to train autonomous vehicles and robots. Additionally, many technical challenges in modern ML involve problems that have been investigated in computational science. The Computational and Information Sciences Directorate (CISD) is well-poised to catalyze important new work that involves collaborations between computational and information sciences, an area that does not currently appear to be pursued.

Other important areas that were not represented relate to trust in AI and a focus on "explainable AI" that facilitates human understanding of AI actions as well as helps to engender trust.

Significant attention is given to AI and ML in research programs across different portfolios at ARL. At present, the scope of these research efforts is rather narrowly focused on technical specialty areas. Fundamental research issues related to innovative ML techniques, AI implementation in resource-constrained environments, and trust and security of AI systems must still be addressed on a broader scale. It is also important to recognize that it is suboptimal to seek algorithmic advances in these areas without due consideration of hardware developments that are taking place in parallel. Given the potential of a disruptive impact of these technologies on Army operations, it is important to develop a comprehensive and integrative research plan in this emerging area. These technologies can have a transformational impact on key elements of Army operations.

Recommendation: The Army Research Laboratory (ARL) should emphasize the identification of a set of fundamental research questions underlying the current research portfolio that can provide a long-term focus in areas of artificial intelligence and machine learning.

Networks and Cyber

The research portfolio in networks and cyber comprises high-quality projects that are well aligned to Army needs. The research is directed at communications modalities, human-robot/machine interactions, and a study of adversarial systems as they relate to cybersecurity. It is not surprising that ML and AI are at the core of many of the ongoing projects. The pursuit of collaborations with internal and external groups performing related research has yielded rich dividends in the research results. Additionally, the approach of using demonstrations to test new concepts brings enhanced visibility to the research program and helps attract early-career researchers into the effort.

In the area of human-robot interactions, advances in narrative generation are significant and have the potential of not only reducing soldier workload but also reducing the bandwidth requirement for tactical networks. The work related to active defense was considered to be exceptionally strong and provides a reduction in the cyber vulnerability of Army vehicles and other cyber-enabled systems.

The approach of having multiple teams address the same problem using different approaches represents a useful research strategy. It provides a direct comparison between the approaches, and the best ideas from each approach can ultimately be leveraged and applied to the common problem. An example of this approach is within the fog computing and tactical distributed ledger projects. Another important research methodology, especially for security issues, is to study systems that have both defense and offense techniques. Once a defense technique is developed, the researchers can then see if an attacker (whether the defense technique is known or not) can be detected by a surveillance system. The "adversarial learning" project is a good example of researchers working on breaking existing norms, with the goal of leveraging what they learn to build better defenses.

Researchers in the networks and cyber areas do not routinely access the computational expertise within their respective larger organization. The quality and impact of research would be enhanced through increased collaboration with computational experts within ARL to leverage their unique and local expertise.

The science of complex computer networks is not well established. In particular, there are issues related to adoption of different protocols on shared communication systems. Army scenarios call for deployment of mobile wireless networks that must operate within a contended environment. In the absence of analytical solutions, emulation of such complex environments provides researchers with insights into the design and understanding of networks dynamics. Researchers in the networks and cyber areas do not routinely access the computational expertise within their respective larger organization. The quality and impact of their work would be enhanced through increased collaboration with computational experts within ARL to leverage their unique and local expertise.

Recommendation: The Army Research Laboratory (ARL) should incorporate tactical network simulations such as the extendable mobile ad hoc network emulator, into its research program. In the absence of analytical solutions, such simulation tools would provide valuable insight into the understanding of network dynamics in complex environments. ARL should consider additional expertise and access to computational resources to facilitate this enhancement.

3

Computational and Atmospheric Sciences

The Panel on Information Science at the Army Research Laboratory (ARL) also conducted its review of selected research and development (R&D) projects of the ARL computational sciences research core competency at Adelphi, Maryland, on June 18-20, 2019. The research areas reviewed were computational sciences and atmospheric sciences. Projects reviewed related to Battlefield Environment Division (BED) atmospheric observations and modeling and computational sciences research, considering both selected, in-depth research presentations and informal discussions surrounding research posters. Projects presented in depth spanned turbulence modeling in complex environments, using a lattice-Boltzmann computational model, understanding the influence of forest canopies on atmospheric dynamics on complex terrain, uncertainty quantification modeling for atomistic-scale modeling, and artificial intelligence/machine learning (AI/ML) at the edge implemented in field programmable gate arrays (FPGAs). In addition, posters spanned atmospheric model prediction via radar data assimilation, meteorological sensor arrays, aircraft vortex and rotor wake characterization, and ML characterization of particle shapes.

While daunting, the repurposing of the ARL mission also presents great opportunities to restate, revise, or create a new vision, which would allow scientists to reevaluate their individual programs in terms of how they fit into the new "big picture." For some projects, the new multi-domain operations (MDO) viewpoint was an immediate and natural fit, while for others, the connections between project objectives and MDO were still being developed. Broadly, the work presented was of high quality, comparable to that conducted at major research universities or leading-edge federal R&D organizations.

Examples of this high-quality research include the hierarchical multiscale (HMS) project, which continues to break new ground, by maintaining and now extending its quality and utility from earlier reviews. Similarly, the AI project, using FPGAs, seeks to build capabilities into Army weaponry (beginning with gunsights), via a framework that involves software, customizable hardware, and reduced convolutional neural nets (CNNs) to meet space, weight, power, and time-to-solution constraints. In addition, the work on ML to characterize particle shapes using scattered light images has the potential for wide applicability throughout aerosol science and in the broad area of chemical or biological agent characterization.

There are a few areas of opportunity. As an enabling, broad-based capability, the computational sciences and BED need to maintain a critical mass of expertise, both for targeted projects and for collaborative engagement with other projects. Similarly, the BED atmospheric modeling research is foundational for many MDO activities, but it would benefit from stronger connections to specific projects.

While it is too early in the deployment of the new strategies to determine which of the BED projects presented during the review are disruptive, two projects have the potential, depending on the path and risks that the projects take over the next several years. The first is the application of ML to characterization of particle shape using scattered light images. As stated earlier, this project, as currently envisioned by the BED team, has the potential for wide applicability throughout aerosol science and in the broad area of chemical or biological agent characterization. A very narrow application of this technology—shape characterization of hydrometeors—could, depending on the research, influence areas such as numerical weather prediction (NWP), where cloud prediction remains a challenge even after 30+ years of microphysics research and testing.

The second is a meteorological sensor array (MSA) application, where chemical detectors are deployed in addition to the meteorological sensors in the simulated urban areas located in the White Sands Missile Range (WSMR) complex. Besides attracting a number of interested atmospheric chemistry researchers, the installation of chemical detectors could allow detailed measurements of chemical dispersion and transport to be made within urban terrain under many different atmospheric conditions. The collection and analysis of such detailed data could be used in multiple AI development programs that require intelligent agents to operate, collaborate, and cooperate with soldiers in diverse environments, including those degraded by adverse weather or adversary concealment and deception strategies. The research teams could conduct a thorough investigation into the feasibility of pursuing these tracks before investing precious resources.

In turn, computational science is becoming a prominent element in training AI/ML systems, such as work using physics-based simulation engines from video games as the source of data to train autonomous vehicles. Further, many of the technical challenges in modern ML involve problems that have been well investigated in computational science work, and emerging research in academia and industry that involves substantive collaborations between computational science and AI/ML is increasingly seen. The Computational and Information Sciences Directorate (CISD) is well-poised to catalyze important new work that involves collaborations between computational and information sciences, an area that does not currently appear to be pursued.

In summary, there is continued research progress, particularly engagement with academic stakeholders via ARL's distributed sites and collaborative academic projects. There is hiring and intellectual development of new postdoctoral associates and staff. ARL needs to continue to foster collaboration across its internal organizational structure. Last, all projects would benefit from clearer metrics for research project success and associated project exit strategies, including transitions that maximize Army benefits.

To provide continuity in review assessments, it would be helpful to identify which projects are part of broad-area efforts or important, single thrusts and which are new starts or continuation of previous projects, and to provide a brief status summary of all projects in progress.

COMPUTATIONAL SCIENCES

Computational science has a rich history at ARL, from pioneering work on ballistic calculations using some of the world's first computers to the laboratory's current role as an essential provider of computational resources for the entire Department of Defense (DoD) high-performance computing (HPC) program. Many ARL-resident research projects are at the leading edge of computational science applications for Army needs, including in areas such as simulation of energetic materials for explosives analysis and the design of advanced armor to protect soldiers and vehicles.

The recent changes in the laboratory and Army organizational structures present new challenges to the continuity of advanced computational research for the Army. These changes include the new emphasis on MDO, along with organizational and programmatic revisions at the laboratory. ARL management appears to be insulating the intellectual work of the technical staff from the administrative details of these widespread changes, and the ARL researchers continue to conduct excellent research despite the uncertainties that invariably arrive with organizational change.

Accomplishments and Advancements

The technical quality of the computational sciences is high, with lower variance in the technical quality than in past reviews. Presented projects were generally cast in the new reference frame of MDO. For some projects, this MDO viewpoint was a natural fit, while for others the connection needed further development. Not surprisingly, the MDO framework will require time for each research effort to adapt, and future review panels could ensure alignment with this emerging set of higher-level DoD guidelines.

A few R&D projects in computational science proved especially worthy of mention, as summarized below.

Methodologies for Scale Bridging in Multiscale Simulation

The hierarchical multiscale (HMS) project continues to conduct relevant research, by maintaining and extending its quality and utility from earlier reviews. HMS has now been extended into the time domain via continuation of modeling of RDX[1] reactivity as an evolutionary multiscale process. This extension to temporal scales, instead of a purely spatial focus, has generated new research work in stochastic modeling and probabilistic ML as applied to the loss and reconstruction of fine-scale microstructural information at each time step. This spatial-temporal extension has supported a number of research exemplars from practical applications (e.g., traction estimation for vehicle mobility in soils, essential to the effective function of the Army's maneuver forces, and the design of next-generation armor enabled by advanced material processes such as additive manufacturing).

Current HMS work in capturing microscale structure of energetic materials is especially promising because this avenue of research increasingly opens new opportunities for simulating the onset of detonation response. In addition to these important advancements on existing ARL multiscale computational technology, the HMS project team is publishing results regularly in high-quality journals and has added a university collaborator to provide additional expertise on uncertainty quantification for the project. As such, this project includes a broad set of key elements of research quality, including high-quality publications, external collaboration, and applications to design, analysis, discovery, and uncertainty quantification. ARL could benefit from collaboration with the University of Illinois (D. Scott Stewart) in this area.

Artificial Intelligence/Machine Learning at the Edge: Inferencing Engines on Field Programmable Gate Array

This promising project concerns development of AI/ML inference engines that can be deployed as a digital chip (application-specific integrated circuit [ASIC]) in Army environments even when network connectivity is not available (e.g., for higher precision targeting). Further, when network connectivity is regained, learning online and training could resume to further enhance target solution quality. Such an ASIC-based online/off-line device could have multiple relevant applications across the cross-functional teams if the underlying systems design and engineering R&D were to be successful.

The technical approach involving a software framework, extensible instruction set architecture, and algorithm redesign/refactoring of convolutional neutral nets (CNNs) seeks to reduce computational costs by an order of magnitude and increase efficiencies to meet space, weight, power, and time-to-solution constraints. This project spans the software-hardware space to deliver performance, portability, and programmability across multiple applications, future CNN algorithms, and future FPGA architectures. Initial results seem encouraging, and there are many possible pathways to transition to the field while advancing the basic research. With improved direction, resources and leveraging of related research, there

[1] RDX is an organic compound with the formula $(O_2NNCH_2)_3$. Chemically, it is classified as a nitramide and is widely used as an explosive.

is the potential for outstanding successes. If not already doing so, ARL needs to consider Google's TensorFlow ML software, which is becoming the industry standard.[2]

Improving Numerical Weather Prediction in Convectively Unstable Environments by Assimilating Radar Observations

The work on improving numerical weather prediction over short time frames through assimilation of radar observations represents innovative research in support of an impactful real-world application.[3] ARL (collaborating with the Combat Capabilities Development Command [CCDC] Aviation and Missile Center, formerly known as AMRDEC) is developing a new mesoscale modeling capability that will provide forecasts in data-sparse regions such as the test facility on Kwajalein Atoll in the Pacific Ocean. Because of the site's unique remote location, current DoD weather capabilities cannot meet these needs.

The ARL approach assimilates radar observations already available at the location into the widely used weather research and forecasting (WRF) prediction model. Radar measurements of reflectivity are then used to infer rates of latent heating for input to WRF. Assessments of the new modeling capability demonstrate increases in probability of correct prediction of weather phenomena through assimilation of radar data by factors up to one order of magnitude.

Challenges and Opportunities

Role of Computational Science at ARL

There is value in a careful definition of the relationship between work in traditional computational science (i.e., large-scale computational simulation based directly on applications implementing scientific principles) and the emerging applications domains of AI (in general) and ML (in particular). AI/ML is a form of computational science, owing to direct correspondence between their respective characteristics. Each is a form of computational simulation, each requires careful consideration of accuracy and uncertainty for an intended use, and each requires due attention to performance and scalability in practical settings.

Depth Versus Breadth

As an enabling, broad-based capability, the computational sciences need to maintain a critical mass of expertise, both for targeted projects and for collaborative engagement with other projects. Areas that have emerged in the past few years, such as AI and data analytics, are very large in scope. Concurrently, the roles of computational science and scientific computation are continuing to expand and evolve. At current staffing levels, ARL computational science may be forced to choose between focusing in depth on a few key areas of most value to the Army or trying to cover a broad range of topics at very limited depth.

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[2] See TensorFlow, "An End-to-End Open Source Machine Learning Platform," https://www.tensorflow.org/, accessed May 11, 2020. TensorFlow is an end-to-end open source platform for machine learning. It has a comprehensive, flexible ecosystem of tools, libraries, and community resources that let researchers push the state of the art in ML and developers easily build and deploy ML-powered applications.

[3] This is an atmospheric sciences project—details can be found in the "Atmospheric Sciences" section later in this chapter.

Internal Collaborative Opportunities

Although many collaborations with academia and industry were reported during the review, the lack of significant computational science interactions with other ARL directorates was notable. With the increasing role of computational science and scientific computation in technical areas under the purview of ARL, this may represent an opportunity for the computational sciences group to become the "go to" division in ARL for advanced computational work. As an illustration, this is, to some extent, the model employed by the Air Force Research Laboratory with its Information Directorate.

Critical Personnel Needs

The computational science R&D portfolio is ambitious and well scoped to serve key needs, but the scope of this portfolio will likely require additional subject-matter expertise, via hiring of new staff, retraining of current staff, or collaboration with external and internal partners. Here are some of the potential areas that may need additional expertise:

1. Expertise in real-time processing and discrete event simulation, when combined with computational science, HPC, and AI, can bring predictive power and decision-making support that otherwise may not be within reach.
2. With an increased emphasis on autonomy, developing staff expertise in computational models for autonomy, complex systems, and emergent behaviors may be required for successful completion of research goals for projects involving autonomous capabilities.
3. Additional expertise in uncertainty quantification (both in computational sciences and battlefield environments), sensitivity analysis, and credibility of computational models will be needed to assess how uncertainty can be propagated through decision chains and how it can be conveyed to battlefield decision-makers.

Collaborations Between Computational and Information Sciences

Simulation is becoming a prominent element in training AI/ML systems, such as work using physics-based simulation engines from video games as the source of data to train autonomous vehicles. Further, many of the technical challenges in modern machine learning involve problems that have been well investigated in computational science work, and emerging research in academia and industry that involves substantive collaborations between computational science and AI/ML is increasingly seen. CISD is poised to catalyze important new work that involves collaborations between computational and information sciences, an area that does not currently appear to be pursued.

ATMOSPHERIC SCIENCES

BED has three main objectives: (1) guide and concentrate foundational research to identify and address Army and DoD scientific and technological gaps; (2) couple fine-scale atmospheric models with novel sensing technologies to enable robust situational understanding; and (3) predict and express environmental impacts on military systems for rapid, human-in-the-loop and autonomous decision making. The 2019 BED review was conducted in the wake of unprecedented changes that have taken place in the Army and ARL within the past year. Because these changes are less than a year old, it will take time for BED scientists to integrate these concepts into their research portfolio and determine whether changes in the direction of projects need to be undertaken. However, with such dramatic changes come equally dramatic opportunities, which are elaborated upon later in this report.

BED's current staffing is 52, which includes 41 government personnel (including three ARL fellows) and 11 contractors. Contract personnel include three visiting senior researchers and three postdoctoral associates. Previous reviews reported that smart use of postdoctoral associates has benefited the quality of BED's research, and that this strategy could be continued, especially if promising candidates can be converted to permanent staff. During fiscal year (FY) 2019, one former postdoctoral associate became a member of BED's government staff.

Accomplishments and Advancements

The research projects presented covered the following topics: (1) turbulence modeling in urban, complex, and forested domains using the lattice-Boltzmann method; (2) influence of a forest canopy on flows in complex terrain; (3) improving numerical weather prediction in convectively unstable environments by assimilating radar observations; (4) simulating turbulent, natural convection using the vortex filament method; (5) meteorological sensor array overview/update; (6) impact of unmanned aerial system rotor-wake interactions on atmospheric sensing capability; (7) aircraft vortex detection and characterization: C-17 formation spacing research project; (8) application of the aerosol Raman spectrometer toward the understanding of ambient atmospheric aerosols; (9) multifidelity uncertainty quantification applied to nonlinear phenomena; and (10) application of machine learning to characterization of particle shape using scattered light images. Updates to projects first described to the ARLTAB in 2017 are indicated as such.

Turbulence Modeling in Urban, Complex, and Forested Domains Using the Lattice-Boltzmann Method

This is an update to a project first described to the ARLTAB in 2017. ARL's assessment is that there is no dominant community model for forecasting microscale flow in the atmospheric boundary layer (ABL). ARL developed the atmospheric boundary layer environment-lattice-Boltzmann method (ABLE-LBM) microscale model for horizontal grid spacing of 1-100 m, temporal resolution on the order of minutes, and efficient use of modern compute accelerators (such as GPGPU). There are computational speed advantages of LBM, and early simulation comparisons with idealized laboratory simulations are promising.

Influence of a Forest Canopy on Flows in Complex Terrain

This project made use of Perdigão, Portugal, field experiment data (May-June 2017), for which ARL scientists played a key role as a planning and principal investigating organization, and during which they emplaced and operated a substantial complement of meteorological towers and instrumentation at the test site. Results were shown for various configurations of WRF model with small horizontal grid spacing, the smallest of which operated on scales of 50 m. The high-resolution simulations produced the most accurate results owing to the impact of high-resolution, corrected land-surface data—not just improved terrain representation.

Improving Numerical Weather Prediction in Convectively Unstable Environments by Assimilating Radar Observations

This project's objective is to improve short-term precipitation forecasts to minimize damage to high-speed projectiles by hydrometeors and was highlighted as an exemplar earlier in this report. The initial location is the Kwajalein Atoll in support of a CCDC Aviation and Missile Center contractor's launch activities. The method adapted a proven (National Oceanic and Atmospheric Administration Earth System Research Laboratory) technique for assimilating radar data into the preforecast period of an NWP model (WRF) for the purposes of improving latent heating profiles, which improves the forecast model representation of clouds, and thus the 0-6 hour forecast of precipitation. A particularly challenging aspect is the lack of surrounding data given the atoll's location. Despite these challenges, fractional skill scores[4] for the model are promising, with best scores coming in the 0-3 hour time frame, when using the longest assimilation window, a very important lead time for the user.

Simulating Turbulent, Natural Convection Using the Vortex Filament Method

This is an update to a project first described to the ARLTAB in 2017. An idealized Lagrangian vorticity model is used to explore new ways of representing turbulence in the presence of localized heating. The flow is represented as vortex filaments with constant circulation. Filaments are constructed piecewise by vortex tubes. Filaments interact, stretching and distorting each other. Additional vortex tubes are introduced in response to diabatic vorticity generation from the heating or to account for interactions between vortex filaments that can result in contorted filament geometries. The energy equation for Lagrangian transport of particles simulates heat transport.

Previous results with this technique showed the ability to reproduce the thermal bubble simulations of Shapiro and Kanak.[5] The nondiffusive Large Eddy Simulation method has produced turbulent flows on a vertically heated wall, and there are plans to study the method over a vertical, viscous heated wall as well as with other geometries. This framework provides a promising method for representing turbulence and heat diffusion in the boundary layer. One application of atmospheric changes forced by localized heating is changes in acoustic signals, potentially affecting communications or "hiding" battlefield resources (see additional comments in the following "Challenges and Opportunities" section).

Meteorological Sensor Array (MSA) Overview/Update

This was an update from the 2016 and 2017 ARLTAB reviews. The MSA is a large, multiyear project designed for acquisition and understanding of atmospheric phenomena in complex terrain. Significant progress in the development of the MSA has been made over the past 2 years despite multiple logistical and operations/maintenance challenges. In 2019, all sensors along the foothills location (Jornada Experimental Range at WSMR) have been installed, and while instruments for the east side of the domain have been purchased and delivered, they have not all been installed. Some cooperative data collection by the U.S. Army Engineer Research and Development Center—Cold Regions Research and Engineering Laboratory and Naval Research Laboratory (NRL) has already taken place, and the next meeting of

[4] The fractions skill score was one of the measures that formed part of the intercomparison of spatial forecast verification methods. The fractions skill score was used to assess a common data set that consisted of real and perturbed WRF model precipitation forecasts, as well as geometric cases.

[5] A. Shapiro and K.M. Kanak, 2002, Vortex formation in ellipsoidal thermal bubbles, *Journal of the Atmospheric Sciences* 59(14):2253-2269.

micrometeorological research groups interested in the study of atmospheric flows over complex terrain at high horizontal resolution will take place at WSMR.[6]

Impact of Unmanned Aerial System Rotor-Wake Interactions on Atmospheric Sensing Capability

This new project was started to support future Army operations in which numerous unmanned aerial systems (UASs) will be operating in the battlefield, with the recognition that environmental conditions will affect their flight operation. In the process of conducting a review of the available studies on the placement and use of environmental and characterization sensors on UASs, the research team found that the literature was surprisingly limited. This justified the need for studying the full parameter space of the sensor-placement problem. The team employed the wind tunnel facility at New Mexico State University to measure particle-size velocimetry for variously configured rotary UASs. Results for forward and vertical flight of a quadcopter-style UAS showed that a rotor-wake interaction region below the multirotor body and rotors precludes the use of in situ sensors. Following these initial results, the team resorted to three-dimensional (3D) printing of various versions of the vehicle in order to test small variations in specifications. Preliminary flow visualization results indicate that in situ sensor placement is limited to the top of the multirotor, and data collected during descent is contaminated by rotor wake. Thus, a correction for velocity measurements will need to be applied that is a function of the vehicle dynamics. Additional work using the faculty, students, and facilities at New Mexico State University is being planned, and the group is aware of other atmospheric UAS efforts.[7]

Aircraft Vortex Detection and Characterization: C-17 Formation Spacing Research Project

The C-17 is one of the "workhorses" involved in airdrop operations supporting the Army. Existing standards for wake turbulence mandate a standard separation between aircraft, and the spacing limits the speed with which multiple drops of equipment and personnel can be accomplished. This project was aimed at reducing the spacing between C-17s participating in airdrops. A firm understanding of the influences of wake vortices is needed to accomplish this task. This multiyear project (set to end in 2020) has collected coupled ground- and air-based light detection and ranging (lidar) measurements of wingtip vortices to characterize atmospheric wind and turbulence vertical profiles. Modeling the behavior of the vortex structure is extremely difficult.

New models, incorporating statistical uncertainty, are being developed and validated using lidar-derived vortex characterization and evolution. The near-term approach is to focus on ground and airborne vortex measurements and development of a new automated vortex detection algorithm for rapid analysis of Doppler lidar data. Data collection in several locations is planned for 2020 using multiple C-17 formation airdrops for model validation. ARL scientists have collaborated with colleagues from Draper Laboratory, Simpson Weather Associates, the Naval Postgraduate School, and ATEC on this project. The ultimate goal is the development of new doctrine that will allow tighter aircraft formation spacing to enhance the speed and efficiency of airdrops.

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[6] For more information about complex terrain observational research and ARL's role in the community, please see H.J.S. Fernando, J. Mann, J.M.L.M. Palma, J.K. Lundquist, R.J. Barthelmie, M. Belo-Pereira, W.O.J. Brown, et al., 2019, The Perdigão: Peering into microscale details of mountain winds, *Bulletin of the American Meteorological Society* 100(5):799-820.

[7] See, for example, the CLOUD-MAP project, http://www.cloud-map.org.

Application of the Aerosol Raman Spectrometer to Understanding Ambient Atmospheric Aerosols

This is an update to a project first described to the ARLTAB in 2017. Raman spectroscopy is an established tool for measuring atmospheric aerosols. The work that was conducted in this area over the review period extends past work and identifies the chemical nature of aerosol species. A new collaboration with New Mexico State University was undertaken, and it is clear that the project is making progress in advancing basic aerosol science. Efforts were made to utilize the MSA at WMSR to correlate aerosol measurements and meteorological parameters. Unique aerosol compositions were measured under different ambient conditions, and attempts were made to correlate composition with sources. The potential future development opportunities for this project are high, particularly as source apportionment activities are continued and efforts to miniaturize the system and expand the available database of spectra that may be used to identify species are undertaken.

Multifidelity Uncertainty Quantification Applied to Nonlinear Phenomena

Cost-conscious use of computational resources in delivering detailed, targeted model guidance is the end goal of this basic research project. In the theoretical framework presented, results from a high-fidelity model (HFM) capture the level of flow detail required; these are regarded as “truth.” The task is to make optimal use of a low-fidelity model (LFM) to explore the critical parameter space (in this case, upstream wind speed and building height). Many simulations of the LFM are used to explore this parameter space, and a “greedy algorithm method” to subselect parameter combinations is based on the LFM solutions. The HFM is run on this reduced set of parameter combinations and a mapping between the LFM and HFM solutions provides a framework for deducing HFM solutions for any arbitrary parameter combination.

While it is in its initial stages, this method has the potential for real-time calculation of detailed environmental situations in the field, and by running the LFM for many parameter combinations near to the first chosen, the uncertainty of the forecast can be quantified, providing a measure of the confidence in the details of the forecast.

Application of Machine Learning to Characterization of Particle Shape Using Scattered Light Images

The characterization of particle shape helps to identify classes of particles that may be present in an environment. Imaging techniques that can be used to help to identify particle shapes are widely available (e.g., scanning electron microscopy analyses), but require sampling followed by analyses in a laboratory setting. The work presented novel research to utilize ML tools and light scattering experiments in order to identify particle shapes. Simulated particle shapes with controlled refractive indices were used to train the code. One-dimensional (1D) light scattering data were subsequently used to test the shape characterization algorithm but were insufficient to predict the particle shapes with high certainty. However, two-dimensional (2D) light scattering data resulted in significant improvements in the identification of shapes.

Challenges and Opportunities

The team believes that in the new MDO environment, project scientists need to have a clearer idea as to what the ultimate application of their project’s results could be. This longer-term view is necessary to articulate project relevance to fellow scientists outside the division as well as to senior leadership, where the latter’s worldview is typically at a high level. An example of one way that a long-term view could be created is presented for the simulating turbulent, natural convection using the vortex filament method project. The project's abstract states that its transition will be "a fundamental tool for studying atmospheric turbulence." In years past, this goal would have been more than adequate, and many scientists familiar with the problem would have applauded it. However, the team suggests taking this several steps further, such as examining *how* the turbulence characterization could be applied to study effects on aerosols, smoke, and propagation. Taking this yet further, the turbulent effects information could be applied to help sensors better detect and identify threats. Ultimately, the application in an MDO environment could inform strategies to counteract deception and concealment strategies employed by a potential near-peer adversary. As shown in this example, the opportunity to reevaluate BED's research portfolio in light of the significant external changes and priority shifts to the ARL research framework provides lead scientists a chance to articulate interdependent relationships (such as in this example) and to make adjustments in cases where they are not as clear as they could be. The team acknowledges that setting these project visions will be more difficult for some projects than for others.

BED researcher interactions with academia continue to be strong and vital, but challenges remain in the engagement with operational entities such as the Air Force, who provide operational weather support for all Army operations except artillery. To make full use of the impactful BED research, it will be necessary to continue dialogues with leadership in the Air Force Director of Weather, in order to keep situational awareness of evolving Air Force requirements and operations and identify possible paths for technology transition. There are also entities within the Air Force outside the weather community who would find BED's environmental research programs very useful. As the MDO doctrine evolves and is integrated into joint operations, it is anticipated that such broadening interactions will bear fruit.

In some respects, the challenges here are not unlike those discussed in the 2017 review. While BED's research programs focus on atmospheric science, programs throughout ARL with environmental sensitivities could use the expertise of BED's scientists. This is especially true within the emphasis area of AI, where many robotic algorithms need to be able to behave properly in degraded environmental conditions in order to provide added value to the soldier in theater. MDO will require such sophistication to defeat countermeasures involving obscurants and other types of concealment that will almost certainly be deployed by a near-peer competitor. As stated earlier, BED as a whole has a great opportunity to reevaluate its position and establish a vision that will keep its portfolio focused on the new and evolving requirements of an MDO operating environment. However, as in 2017, resource allocation continues to be a challenge. BED could continue to leverage use of as many avenues for assistance for its projects as feasible. This will ensure that personnel can strike the right balance between the environment-centric projects within the division and the environmentally sensitive ones outside the division. It is worth restating that, while full BED collaboration with other laboratory projects has the potential for great impact on these other projects, it will put a significant strain on BED's existing resources.

Turbulence Modeling in Urban, Complex, and Forested Domains Using the Lattice-Boltzmann Method

Although the work is sound and has clear implications for supporting future Army operations in challenging operational environments, some important issues can be raised about the future of this effort. For instance, it was not obvious from the presentation what the operational testing strategy and success criteria would be once model runs are conducted using detailed observational field data. Examples of the types of questions that could be asked are: How many different configurations need to be tested and for how many different types of flows? How could observations be used to guide the initialization of the model? How many different data sets need to be used for comparison? Without this type of structure, the project runs the risk of becoming open-ended.

Influence of a Forest Canopy on Flows in Complex Terrain

Several limitations or future challenges were identified. First, a number of modifications to the model's preprocessing data files were required (e.g., changes to land-use categories based on lidar data to account for complex vegetation along the hillsides). How could such modifications be made in areas that do not have access to lidar? Second, while the 50-meter resolution version of WRF produced the most accurate simulations of small-scale flows along the parallel ridges there, upslope case simulations had some accuracy issues with temperature and wind direction, and there were similar problems for downslope cases. Third, several sets of field observations were shown that did not fit previously accepted conceptual models for upslope and downslope flows. All of these require additional analysis and study.

Improving Numerical Weather Prediction in Convectively Unstable Environments by Assimilating Radar Observations

The principal investigator (PI) is investigating the broader adaptability of this project to other Army applications; use of satellite data in addition to the radar will allow the technique to be applied in locations without conventional surface observations and weather radar. The PI is aware of research into satellite-based convective initiation methods such as cloud-top cooling, and is looking to engage the Federal Aviation Administration and Massachusetts Institute of Technology's Lincoln Laboratory about using the Corridor Integrated Weather System (CIWS), which applies satellite imagery for short-range (0-2 hour) projections supporting air traffic management operations in U.S. offshore regions, to explore enhancing the predictability of mesoscale phenomena in data-sparse regions. Because the Air Force is also being provided offshore CIWS data, the PI wants to investigate the possibility of tapping into that data feed to examine results and evaluate the technique. ARL needs to also tap into work of the National Aeronautics and Space Administration and Department of Energy (DOE) in the area of NWP.

Meteorological Sensor Array Overview/Update

In addition to potential international research collaborations, the group has proposed instrumenting space within the MSA that has buildings to create a unique, urban-styled test-bed area within WSMR that can provide valuable meteorological data within dense urban environments. Such a test-bed area could potentially lead to collaborative opportunities, with researchers investigating the use of robotic vehicles in urban environments. The test-bed could provide them with detailed meteorological data that can be used to evaluate the effects of dust and other obscurants on unmanned vehicle operations (e.g., in the AI for maneuver and mobility project). These urban test-bed data could also be valuable for developmental testing of the ABLE-LBM model.

Application of Machine Learning to Characterization of Particle Shape Using Scattered Light Images

The potential that this work provides for enhancing Army research and broader impacts in the scientific community is exceptionally high. Of particular note is the potential to enable the identification of multicomponent materials. Further coupling of the particle-shape characterization technique (for initial screening) with a fast-chemical characterization technique would enable significant enhancements in particle analyses. As such, the project's potential as a disruptive technology is exceptionally high.

OVERALL QUALITY OF THE WORK

Computational Sciences

The technical quality of the computational sciences work represented in the presentations and posters was generally high. Research papers are being published in high-quality journals and being presented at the leading conferences. The ARL staff demonstrated deep knowledge in many of the areas in which they are working, through their descriptions of their research and in providing answers to questions. There were also several good examples of effective collaboration with external experts in areas in which ARL seeks to develop internal capability.

The research quality of the material presented was high—comparable to R&D conducted in leading universities and within the federal national security complex. The particular exemplars detailed in the "Accomplishments and Advancements" section above would serve as typical research projects in U.S. university, federal, or industrial venues.

The projects presented demonstrate an appropriately broad appreciation of the relevant scientific principles, as well as a clear understanding of external research results. The three exemplar projects cited above are excellent illustrations of this, given that they each demonstrate connections to external research results and to appropriate advanced research methods.

Equipment needs are mostly computational, and ARL provides excellent support for these research requirements. The numerical methods utilized in the projects that were presented are appropriate for the scope of work as proposed and are representative of the advanced techniques used outside the institution.

The research teams are composed of high-quality personnel with relevant subject matter expertise for the associated projects. The team personnel reflect a good mix of junior, mid-career, and senior staff, and the research outcomes appear to be both ambitious and feasible

The computational sciences activities are very well supported through the ARL Supercomputing Research Center, which includes both a DoD Supercomputing Research Center and a DoD Data Analysis and Assessment Center. However, ARL could further collaborate with supercomputing programs at other DoD and DOE laboratories.

The research projects presented do employ appropriate theoretical and computational methods, and those projects that involve experimental validation results, or that use existing sensors (e.g., the radar project cited as an exemplar above), generate data sets appropriate to the various project needs.

Each of the exemplar projects is a good illustration of especially promising projects. While none of these were obvious candidates for "disruptive" status, each showed particular promise in important characterizations such as "potentially game-changing" or "especially cost-effective for the Army."

As noted elsewhere, future reviews would benefit from a brief summary of the state of all projects, not just those presented at the review. This would allow a more holistic assessment of ARL's work and the potential for disruptions.

Atmospheric Sciences

The technical quality of the BED research represented in the presentations and posters was generally high. Researchers are very familiar with the underlying science and cognizant of research conducted elsewhere; in some cases, BED researchers are in active dialogue or collaborating with researchers outside the laboratory. In all cases, the researchers are aware of the potential challenges associated with their projects. As noted in previous reports, the incorporation of researchers from different disciplines into BED projects is notable. In project updates, a clearer delineation of "new" versus "old" results needs to be made, as results presented in several of these looked similar (although not identical) to those presented in 2017.

The overall scientific quality of the work is high, comparable to research conducted at successful university, government, and industry labs. The majority of the work described in the "Accomplishments and Advancements" section above is comparable to research projects in U.S. university, federal, or industrial venues.

The projects demonstrated a broad appreciation of relevant scientific principles, as well as an awareness and clear understanding of external research results.

The numerical methods used in the projects that were presented are appropriate for the scope of work proposed and are representative of advanced techniques used outside ARL.

The research teams are high quality, with relevant subject matter expertise for the projects, either organic or through collaborative arrangements. The teams have an appropriate mix of junior, mid-career, and senior staff, and are suitably organized for the research challenges presented.

The BED research projects that are computationally intensive appear to have good resource support. The MSA project has made good progress in fielding a vast array of observational equipment, although there are some logistical issues associated with the continuing operation and maintenance of the fielded equipment. The research projects presented employ the appropriate theoretical and computational methods, and while several projects involving experimental validation are just now beginning to utilize observational data, the necessary plans are in place to move those forward. Those using existing sensors, such as the radar assimilation project described earlier, have generated data sets appropriate to the project's needs.

The radar assimilation project and the C-17 vortex detection and characterization project are likely the closest to transition, although neither is immediately ready. These projects are different from those identified earlier as being potentially "disruptive" in an R&D sense, as the disruptive projects are not as far along in their development. Future reviews would benefit from a brief summary of the state of all projects, not just those presented at the review. This would allow a more holistic assessment of ARL's work and the identification of potentially disruptive technology.

RECOMMENDATIONS

Computational Sciences

The research portfolio presented is of high quality and is comparable to that expected from a high-quality university research program or from a leading-edge federal R&D organization. The teams are making effective use of available resources, and a good mix of diverse projects in computational science were presented, ranging from practical projects that generate cost-effective results by integrating various established technologies to projects where intellectual venues that have rarely been explored are being developed for particular Army needs arising from the MDO frame of reference.

Discussions with ARL managers indicated that while organizational and programmatic changes are occurring at nearly all levels of the Army, the goal of research program continuity is being realized despite these changes, but that challenges remain to be overcome. These challenges include the usual concerns of available personnel and financial resources, the relocation of research projects that do not fit the fundamental research exploratory nature of ARL's mission, and uncertainties about the relationship between traditional computational science methods and emerging AI/ML techniques that both support and supplant established methods.

The presentations demonstrate that ARL is leveraging synergies between its various research core competencies (e.g., the AI-FPGA project mentioned above). This development is guided by Army needs and could lead to critical breakthroughs. While advances in technologies or the human factors of the battlefield/edge processes/logistics are needed, innovation at their nexus that are guided by MDO needs present new opportunities.

Recommendation: With the mission of combat capability development, the Army Research Laboratory (ARL) should leverage synergies within the computational sciences and the networks and information sciences research core competencies—for example, artificial intelligence (AI), data science, high-performance computing, networks, and battlefield environment effects. Further, such an approach should be applied by ARL across other research areas—for example, human sciences and AI—which could be a force multiplier that may not be possible otherwise.

Atmospheric Sciences

Atmospheric science, particularly meteorology and atmospheric chemistry, is critically important to creating disruptive technologies that have broad applicability to the Army needs. ARL research in these areas is strong overall. The impact of ARL atmospheric science research can be enhanced through compelling communication of its relevance within the umbrella of ARL, and within the context of the overall Army needs. A striking example of the need for integration of meteorology from the beginning of a project is in operationalizing MDO, in which all of the envisioned enabling technologies are potentially vulnerable in some way to degradation from environmental factors on the battlefield and environmentally based countermeasures employed by our adversaries.

Thus, strategic integration of BED research thrusts with complementary research in other areas is encouraged. One mechanism for accomplishing this is the use of the network and information sciences and computational sciences taxonomy to optimize the impact of the BED expertise and limited resources, while providing opportunities for critical research in environmental research and across disciplines. There are numerous opportunities to advance fundamental science in these disciplines while encouraging multidisciplinary collaboration. This trend is one that is consistent with leading edge, collaborative approaches that the broader scientific community is undertaking in addressing grand-challenge questions and promoting use-inspired research.

There are a few areas of opportunity. As an enabling, broad-based capability, the computational sciences and BED need to maintain a critical mass of expertise, both for targeted projects and for collaborative engagement with other projects. Similarly, the BED atmospheric modeling research is foundational for many MDO activities, but it would benefit from stronger connections to specific projects. Last, efforts to date to include atmospheric considerations in other venues is commendable. However, it is important to develop new collaborations given that environmental phenomena are crosscutting and affect nearly every Army operation.

Recommendation: The Army Research Laboratory (ARL) should evaluate the potential for environmental integration at the start of a project's activities. ARL should consider such work that could lead to novel basic science approaches and be transformative in the broader scientific community, particularly in the use of computational techniques and large data sets to enhance decision making, technology use, or operational efficiencies.

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Human Sciences

The Panel on Human Factors Sciences at the Army Research Laboratory (ARL) conducted its review of selected research and development (R&D) projects of ARL's human sciences (HS) core competency area at the Aberdeen Proving Ground, Maryland, on May 29-31, 2019. The HS project areas reviewed were human-autonomy team interactions and humans understanding autonomy; autonomy understanding humans and estimating human-autonomy team outcomes; human interest detection; cyber science and kinesiology; neuroscience, training effectiveness, and strengthening teamwork for robust operations with novel groups (STRONG).

ARL's HS core competency is focused on identifying, creating, and transitioning scientific discoveries and technological innovations underlying three research areas: cognitive dominance,[1] readiness for technological complexity, and teaming overmatch.[2] These areas are critical to the U.S. Army's future technological superiority. This core competency area concentrates on high-risk and high-payoff transformational basic research with potential for having revolutionary impacts on the Army's warfighting capabilities. The ultimate goal is to contribute to the creation of disruptive and game-changing soldier-centric technologies for the Army, while also anticipating technological surprises from potential adversaries.

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[1] As described by ARL, the cognitive dominance research area involves the following: Foreign powers are exploiting approaches to enhance soldiers' mental capabilities that the U.S. military has determined are outside the ethical standards of operations. Without an alternative approach, the U.S. military risks losing its advantage in battlefield cognition. Merging expertise from DoD's leading nonmedical neuroscience R&D group with expertise in machine learning, artificial intelligence, cognitive sciences, and learning sciences, CCDC ARL is leading the development of the neuro-technologies to ensure that soldiers cognitively dominate the battlefield. Technology has capabilities that even "super-humans" will not be able to achieve. Thus, CCDC ARL's work focuses on mixed human-technology approaches that optimally exploit human and technology capabilities to create faster, more effective cognitive processing in the field. Innovations in this area are expected to seamlessly integrate soldiers and technology to produce more accurate situational awareness and situational understanding; faster, more effective decision making; and greater agility to handle threats.

[2] As described by ARL, teaming overmatch refers to the following: From team cohesion and coordination, to organizational communications and shared situation awareness, through collective action within societies, group dynamics are critical to determining success in every operational environment our soldiers face. Foreign powers are exploiting knowledge of how groups of people function as well as the capabilities of artificial intelligence to shape the environment and develop operational advantages. Without countercapabilities focused on optimally exploiting group dynamics in order to shape the environment and create windows of opportunity to provide overmatch, the United States will remain at a disadvantage. In response, CCDC ARL is conceiving of technologies that enable U.S. Army units to predict and outperform their adversaries, including technologies focused on within-group (friendly) dynamics as well as prediction of enemy and civilian group behaviors.

HUMAN-AUTONOMY TEAM INTERACTIONS AND HUMANS UNDERSTANDING AUTONOMY

ARL is preparing for a future where both humans and machines are working together toward operational goals via human-autonomy teaming. ARL's research is critical for making autonomy work for the Army. The field of human-autonomy teaming is relatively new, and ARL has an opportunity to conceptually and empirically define the trajectory for this domain of interest. There is recognition that for effective human-autonomy teams, the autonomy needs to complement and respond to human needs and responsibilities. Overall goals of ARL human-autonomy teaming work are aimed at greater team resilience with robust, adaptive performance; fast, dynamic team reconfiguration; faster, more informed decision making; and reduced risk to soldiers. Current and future work focused on these goals is likely to lead to more efficient, effective, and high-performing human-autonomy teams.

Now part of the Army Futures Command (AFC), recent changes within ARL allow for new opportunities relating to human-autonomy teaming. ARL is focused on performing basic research that contributes to what is referred to by ARL leadership as "foundational" research—described as the integration of both basic and applied work. This work encompasses both sides of the human-autonomy teaming paradigm, autonomy understanding humans and humans understanding autonomy. There is a clear understanding at multiple levels within ARL that it is necessary to focus on both the technology and the human, yet the emphasis is rightly on human performance and outcomes (especially within the HS core competency area). Specific to the HS core competency within ARL, the human-autonomy teaming group operates under the teaming overmatch thread of work, and this includes two substreams of work termed "understanding and predicting group dynamics" and "creating group synergies." Work being conducted within these areas includes understanding variability in humans, variability in human-related technologies, human-artificial intelligence (AI) teamwork, human-robot interaction, and crew enhancement.

Accomplishments and Advancements

There are many crosscutting human-autonomy teaming projects occurring throughout ARL that are bettering the human experience in human-autonomy teaming and are working toward the development of real human-autonomy teams, where the autonomy is a fully functioning technology.

ARL has developed robust, contextualized human-autonomy teaming research laboratories. ARL has developed state-of-the-art synthetic task environments and data collection platforms through Cyber-Human Integrated Modeling and Experimentation Range Army (CHIMERA) and Information for Mixed Squads Laboratory (INFORMS). INFORMS has the potential to gather data on platoon-size teams (dual 7-person crews) that does not exist anywhere else. This could lead to very interesting science on platoon-size interactions, shared mental models, and attention allocation. In addition, the CHIMERA laboratory has outstanding metrics collection capabilities for cyber-human systems studies. ARL has significant experience and investment in neurophysiological measures to infer human states, as well as instrumented laboratories and simulation capabilities. Such advanced facilities promise to provide the ecological validity and experimental control needed to generate empirical evidence to address research questions and advance the science of human-technology integration.

ARL's research portfolio includes an ambitious mix of human sciences and enabling autonomy. ARL is taking on an ambitious research portfolio relating to multiple aspects of human-autonomy teaming. As outlined earlier, both humans and technology need to be studied separately and in concert with each other to further human-autonomy teaming, and ARL is doing research that falls within this purview. Key problems are being explored, including autonomy adapting to humans, autonomy understanding humans, trust, spatial mental models, and estimating team outcomes.

ARL has identified expertise gaps in the composition of their research team and has a plan in place to enhance internal expertise while connecting with the broader community via the STRONG program.

STRONG refers to strengthening teamwork for robust operations in novel groups, with the goal of developing the foundation for enhanced teamwork within heterogeneous human-intelligent agent teams. The STRONG program is an innovative way to elicit expert opinion, outside ARL, to inform the human-autonomy teaming work that will occur internal and external to ARL. This unique and highly collaborative method to encourage constant and direct communication between academia and government could be examined as a future model of funding within other departments and agencies of the government. A critical introspective assessment of the successes and failures of the STRONG program will need to be conducted to ensure that the model is adjusted for maximum productivity.

Challenges and Opportunities

An Approach to Foundational Research with Unique Access to Contexts

ARL leadership has a clear and correct understanding that the scientific questions to be pursued may be shaped by or result in changes to its long-standing doctrine. The purpose of this scientific approach is not just to serve the outbuilding of technological capabilities, which may be co-opted by competitors or enemy combatants, but also to inform the overall doctrine, organization, and strategy of the Army. As previously noted, ARL is tasked with doing foundational research involving the interaction of basic and applied research. This seems an admirable goal, but the concept needs to be better defined, as both basic and applied research meld into each other, making empirically setting and testing specific goals of each project difficult.

The most difficult questions to answer are also those that are most difficult to measure appropriately, least likely to be co-opted, and most likely to provide advantage against adversaries. These include questions that will help clarify how the myriad sociotechnical factors in real-world environments shape human decision making with adversaries, where superiority of doctrine relies on emergent outcomes that derive from values, strategy, and creativity, rather than predetermined processes and mechanistic outcomes. ARL is investigating these types of questions and could beneficially conduct more work on adversarial human-autonomy teaming research. Researchers with expertise in the HS, especially in human factors, cognitive psychology, industrial and organizational psychology, and systems engineering, are best able to address these important questions, and ARL has shown leadership by building a staff with these scientific capabilities.

ARL faces extremely challenging human-autonomy problems and has unique access to the operational environments and subject matter experts to best understand the novel problems that will arise in the most complex human-autonomy teaming environments. These operational environments are a platform for providing real-world context and evaluation of human-autonomy teaming initiatives.

Continuing to Build In-House Expertise in Team Science

There is an opportunity to continue to build team science expertise in house. In order to successfully study human-autonomy teaming and provide cutting-edge applications, it is necessary to have a deep knowledge of traditional and nontraditional teaming approaches. Here nontraditional teaming is meant to indicate human-autonomous teaming. There is some expertise residing in ARL specific to human-autonomy teaming, but there is a significant need for more such expertise. Specifically, there seems to be a lack of expertise relating to human-human teaming that is needed to inform human-autonomy teaming. It is necessary to have experts in house who understand the fundamentals of teamwork to advance the domain of human-autonomy teaming.

Continuing to Build Team Science Expertise Externally

ARL's *IEEE Brain* publication[3] could be leveraged to continue to develop specific areas of research such as the human-machine interface and team communication within the paradigm of human-autonomy teaming. These team science-specific areas could be defined in detail to provide an organizational landscape for the future trajectory of human-autonomy teaming. These areas will also help to specifically outline short- and long-term goals. It is also necessary to keep sight of the importance of human-human teaming in studying the paradigm of human-autonomy teaming. It is expected that the STRONG program will help bolster external team science expertise.

Directing and Using Unique Access for Human-Autonomy Teaming

To achieve its stated goals, ARL is in an advantageous position with unique access to the U.S. Army's warfighter environment, soldiers as study participants and subject matter experts, and standardized training programs to provide controlled baselines for scientific research. ARL thus has strong potential to lead the research of leveraging autonomy and AI in high-criticality complex work environments.

ARL could make more use of this access to ensure that its researchers immerse themselves and become more familiar with actual operations. In addition, it would be beneficial if there were continued interactions between customers, users, and researchers throughout projects to realize possible need for mid-course corrections. It would also be beneficial if more military personnel with combat experience were integrated into these research teams. Much of the research presented was conducted using college students as participants, instead of military personnel. ARL could either use more military personnel for experimental studies or use college students with greater knowledge of the military problem space. College Reserve Officer Training Corps programs are a much better resource for these studies than college students in other departments are.

Unbiasing Data for Human-Autonomy Teaming

The main challenge will be to carefully design unbiased experimental scenarios for ARL's data collection environments that are not an echo chamber for proving current Army strategy or technology (although it may also be used for these purposes). The research needs to be geared for rapid advancement rooted in research questions that will provide the most return on investment for the current science.

Addressing this challenge will involve starting with fundamental science questions and then figuring out how they apply to the Army needs as opposed to the other way around. To do disruptive work, ARL needs to start at the basic science level instead of the applied problem. The latter may be easier to convey to Army stakeholders but is likely to lead to myopic results for the scientific community.

Addressing this challenge will also require input from experts in human subjects' research with synthetic task environments. The challenge is not just to advance science and technology but also to advance understanding of whether or not the U.S. Army has the superior doctrine underlying how the technology is used. Understanding how to study and integrate critical work environment factors with knowledge of human capabilities and limitations requires specific expertise and leadership from human factors and systems engineering experts.

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[3] See IEEE Brain, "Enhancing Human-Agent Teaming with Individualized, Adaptive Technologies: A Discussion of Critical Scientific Questions," https://brain.ieee.org/brain-storm/enhancing-human-agent-teaming, accessed May 11, 2020.

Therefore, basic or fundamental science questions and theories needs to be pursued by ARL, but this could be done in the context of applied or "actual" operations. Such fundamental research, perhaps on nonmilitary study participants, might be pursued first, and then be followed up with further tests in military personnel.

Balancing Near-Term Problems with Long-Term Vision

A challenge is matching the ambitious long-term vision communicated by ARL leadership with the demands of addressing near-term problems of human-autonomy teaming. The researchers seem to face a tension between addressing problems on human-autonomy teaming that affect warfighters using near-term robotic and AI technologies on one hand, and doing the basic research that leads to the kind of scholarly work and to foundational breakthroughs in human-autonomy teaming on the other hand. There seems to be a tension between trying to do long-term foundational work but at the same time having to support the development of many short-term deliverables.

AUTONOMY UNDERSTANDING HUMANS AND ESTIMATING HUMAN-AUTONOMY TEAM OUTCOMES

ARL is responsible for a wide range of interdisciplinary research projects that bring state-of-the-art research to bear on Army-unique problems. Within the HS core competency area, many projects contain an autonomy component that is designed to assess or predict human-human or human-autonomy teaming. The current portfolio focuses on specific aspects of these problems. Machine learning (ML) application focuses on fusion of multimodal sensory input for online learning or off-line modeling. Experimental and simulated frameworks leverage in situ data collection to evaluate theoretical models in real-world application. Projects in this domain include human AI interactions for intelligent squad weapons, cycle of learning for autonomous systems, and information for mixed-squad laboratories. The project on human-AI interactions for intelligent squad weapons uses advanced sensing algorithms to perform automated target recognition, which is then displayed on a scope or a heads-up display. The cycle of learning for the autonomous systems project uses Learning from Demonstration (LfD) to program and refine a quad-rotor-landing algorithm. INFORMS is a dual 7-person crew station facility that simulates auditory, tactile, haptic, and visual input during an operational context. It is networked to other ARL facilities at the Aberdeen Proving Ground, for distributed operations simulation. INFORMS enables the study of human-agent teaming during operations.

Additional projects under way incorporate either state-of-the-art or black box ML. Researchers interested in human performance prediction and human interest detection (HID) leverage ML techniques in sensor fusion for human understanding. These projects include convolutional neural networks used to measure human performance through prediction of p300 variability,[4] soldier gaze tracking and neural activity used to passively detect salient environment features at a team level, and methods for understanding the quality of human communications tools for annotating human conversations.

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[4] p300 is an event-related potential component elicited in the process of decision making. It is considered to be an endogenous potential, as its occurrence links not to the physical attributes of a stimulus, but to a person's reaction to it. More specifically, the p300 is thought to reflect processes involved in stimulus evaluation or categorization.

Accomplishments and Advancements

The goals of the HS core competency area is unique in that research challenges lie in the application of innovations. The ability to apply autonomy in the presence of real-world noise at real-time time scales is challenging. The oversimplification and constraint removal traditionally employed by academic researchers misaligns their research to the problems faced by the military. All the HS researchers could consider the challenges and complexities of autonomy in real-world tasks.

Infrastructure, which is key in evaluating research in the Army context, is one of the biggest strengths of the HS research teams. INFORMS is a valuable and unique resource. It simulates platoon-level crew stations with haptics, auditory, display, and tactile interactions. It was conceived as a platform for testing crew interactions with intelligent agents. It provides an additional opportunity to study crew interactions and leverage insights into innovations in rapid prototyping. The Innovations Commons is an instrumented, distributed sensing environment that allows for the capture of more realistic data sets.

The neuroimaging laboratory enables research on neural input during physical activities (as would be required in this context). Several prototype electrodes are being constructed with different signal and noise characteristics. The project included development of a "phantom head" for generating controllable synthetic data, as well as development of new electrodes (using materials science) that are robust to noise. This is an important step forward for the Army because it will need to solve these challenges if it is to use electroencephalogram (EEG) sensing in the field. The phantom head allows the generation of ground truth data that can be used to validate models.

Autonomy and computation are key to research that allows for prediction in noisy, real-world conditions. Human motion is captured during walking or running and can be replayed on a hexapod for simulating human walking motions, which allows for simulation of real-world noise and the study of the motion artifact.

The project on human-AI interactions for intelligent squad weapons seeks to use advanced sensing algorithms to perform automated target recognition. Such algorithms could leverage video and other multimodal input to identify targets on the heads-up display targets and infer whether these targets are friend or foe. The algorithms would not be limited to target recognition and could grow as new capabilities and needs unfold. The research team's key contribution is a system that could continuously acquire and store real field data for labeling and training of improved perception algorithms. Rather than try to develop better algorithms, this team seeks to fill a significant void by having a ubiquitous platform collect the right relevant data for humans to annotate at a desk or in the field in real time. The project has the right mix of AI and human science-focused researchers. The team understands well its competencies and is focused properly on an exciting opportunity to design a potentially game-changing system to acquire, curate, and leverage powerful-targeted data for training off-the-shelf computer vision algorithms. The intent is to collect data at large scale and under more complex and naturalistic task environments with novel sensors. The researchers have a solid research plan and are well-poised to deliver on a project that they are just ramping up. If the team succeeds, it will have the evidence it needs to bring support to investment in the underrepresented and overlooked area of data acquisition and curation mechanisms to feed ML algorithms. While intelligence analysts seek data for their own purposes, the process of acquiring and labeling data for training ML algorithms is different and requires its own skill set and infrastructure. This project could revolutionize the way the Army views AI/ML and, in turn, the latent power that could be unlocked by investing in such projects.

The project on cycle of learning for autonomous systems leverages learning by demonstration for robot control. The researchers take the realistic position that achieving ubiquitous robots in the hands of end-users will require a multiphased, multimodal approach to situated learning. This project presents a cyclic architecture at four levels in which (1) a robot is taught a skill first by a human demonstrating said task; (2) the human shifts to intervening in the robot attempting that task (e.g., via direct control) when failure occurs or is about to occur; (3) the human provides a grade (i.e., a reinforcement signal) to guide the robot toward better behavior; and (4) the robot refines its own policy based upon a human-encoded grading system.[5] The robot moves from level 1 to 4 as it gains proficiency, ultimately becoming autonomous.

A significant achievement includes the collection and management of large data sets (here, large means something significantly bigger than average). Ambitious data collection activities—over time, between and within subjects, in the field—with target populations have created a number of large data sets that will be used to drive ML and simulation. The team has access to good information technology infrastructure to store and protect these organized and time-stamped infrastructure components. These researchers are pioneering something new.

Researchers involved in the project on brain dynamics of driver-passenger communication presented an interesting methodology. The goal is to identify neural mechanisms that indicate effective verbal communication. The researchers observe EEG changes during communication with the goal of identifying physiological markers that relate to successful communication. Such information can perhaps be used to appropriately adjust autonomy based on human performance.

The research project on p300-passive detection of situation awareness for the battlefield environment is a good opportunity for the HS core competency area. The team demonstrates the relevant expertise to attack the problem and understanding of the limitations of current methods (e.g., task specificity, subject specificity, noise, and requirements for large data sets). The neural encoding approach shows great promise in this area, and is methodologically sound. The task selected for testing (stimuli with human targets with and without weapons) was Army-relevant.

Challenges and Opportunities

Researchers are expanding the scope of autonomy understanding individuals to include predictions of human-autonomy team outcomes. This effort is less mature, and researchers are focused on what data to collect to evaluate team effectiveness and outcomes. Initial efforts involved looking at communication effectiveness and resulted in the creation of a tool to annotate human conversations. A study of human-to-human communication under higher cognitive workloads provided an opportunity to evaluate the usefulness of the tool. The goal is to understand how to evaluate mixed team effectiveness, possibly utilizing methods identified for evaluating individual or exclusively human team performance. The choice of this approach to measure communication effectiveness is not well motivated. No evidence is presented that supports this as the most promising measure—physiological or otherwise. Rather, this approach seems to be selected based on the researcher's interest and background.

INFORMS is a valuable and unique resource. Because of the fidelity that can be achieved, there is a danger that this laboratory could be devoted to training. It is important that this facility be reserved for research use.

Although the approach demonstrated in the cycle of learning is appropriate, none of this research is particularly novel. Each phase of interaction has been considered explicitly, repeatedly, and thoroughly in prior literature. More than 10 years ago, researchers started exploring multiphased interactions for robot learning architectures that consider learning from both observation and demonstration. The deep-learning algorithm Deep Training an Agent Manually via Evaluative Reinforcement (Deep TAMER) itself is not particularly game changing. Over the past 5 to 10 years, the field of AI has seen numerous reboots of algorithms that leverage neural networks as a preprocessing step or in substitution for a different function approximation technique. These steps are important, but they are nonetheless incremental.

With respect to the project on cycle of learning, the team's primary demonstration mechanism was teaching an unmanned aerial vehicle (UAV) to land on top of an armored troop transport. UAVs today

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[5] N.R. Waytowich, V.G. Goecks, and V.J. Lawhern, 2018, Cycle-of-learning for autonomous systems from human interaction, https://arxiv.org/abs/1808.09572.

typically ship with autopilot controls and could easily be programmed through nonlearning techniques to find a landing zone and land without collision just as commercial aircraft can leverage instrument landing systems. It became apparent that the genesis of trying to apply LfD to this landing problem was from the military, because soldiers were struggling to manually land a UAV on the back of their vehicle, and wanted this research team to solve that problem. The research team's strength is developing LfD algorithms. Thus, the team is left with either trying to develop a solution outside its research focus or trying to use LfD algorithms for a problem that does not warrant such techniques. The program would benefit by management direction to emphasize human science-focused problems, while better matching open source ML or engineering approaches to the specific research problems. Although this issue was primarily observed in one project, all projects that leverage black box ML techniques or those that require novel ML techniques could create a distraction around the existing dedicated focus on human sciences research.

HUMAN INTEREST DETECTION

The specific objective of the human interest detection (HID) program is to use passively collected data from human sensory systems in the field to make conclusions about the elements of a sensed scene that are of interest to viewers (e.g., discovering blind spots and focusing attention). In team situations, this effort may involve combining diverse views into a single model of the scene.

The wider objective is to develop the infrastructure for real-world neuroscience. The infrastructure will allow both a broader range of sensing inputs and analytics to be incorporated, and it will support future applications built on the infrastructure. HID was listed as a future program, but the current effort emanates from the Cognition and Ergonomics Collaborative Technology Alliance (CTA), which is an approximately 10-year effort.[6] Outputs from that CTA—for example, a convolutional network for EEG-based brain-computer interfaces (EEGNet)—are being leveraged for this new program.

Examples of work that was presented include detection of objects of interest from multiple streams of data collected from the visual system of soldiers and EEG, detection of instances of target detection by a human using EEG (p300 visual-evoked potentials), and improved EEG signal acquisition.

Accomplishments and Advancements

HID is an important area in the ARL research program. The research is uniquely applying real-world neuroscience and AI to the area of attention. Building on a 10-year or so neuroscience program, the research team is taking the kinds of risks that are appropriate. These efforts and risks include the following: taking a plausible but rich use-case set and demonstrating feasibility, understanding and modeling HID, and exploring alternative inputs and algorithmic approaches over time to find solutions that will scale. There has already been successful technology transfer of some of the HID team's work. The new HID program is leveraging innovative tools developed from this past work. The HID effort is performed in partnership with external laboratories and contractors. The studies and results in the HID area are interesting and constitute an exciting start on the journey toward the new HID program. The HID research team's platform approach is an effective way to manage the risk of failure in a particular line of exploration by ensuring that work that was developed and documented can be reused if the project needs to pivot to take another direction.

[6] See CaN CTA, "The Cognition and Neuroergonomics Collaborative Technology Alliance," https://cancta.net, accessed May 11, 2020.

The HID team on EEGNet and studies on detection of p300 for target detection in humans did significant feasibility work. The convolutional neural network implemented by the HID team for EEGNet is a useful tool for this research and other studies.[7] The merit of the effort transcends the specific project shown, in that it paves the way for similar future real-world neuroscience.

Challenges and Opportunities

ARL is in the early days on the HID program, so it is not too surprising that the specific projects presented would require several technical obstacles be overcome. These obstacles include the need for more efficient and convenient collection of data in the field (especially EEG signals), overcoming motion artifacts in the data, and the use of adaptive decision fusion for decision making.

There are several projects in other programs that are not officially under the umbrella of HID but could be included in the exploration of this area. As the HID research team grows the program, leveraging links to related projects could be advantageous. HID researchers are already coordinating across some other programs and teams.

Members of the HID research team observed, rightly, that deployment of their algorithms and methods will depend on leveraging lines of research undertaken by external companies, and on emerging commercial technical solutions and tools. For example, IBM, Facebook, Microsoft, and others are working on a variety of EEG and other wireless sensing devices. The HID team understands that there is an opportunity to find better ways to influence industry to ensure that technologies that will be needed to deploy HID solutions will be available when needed. This understanding may lead to the development of a new model of interaction with industry in the area of HID.

In the future it will be important to explore and prioritize other inputs for HID, such as speech between members of soldier teams, auditory input (which influences visual attention), and situational and automatic emotional states and responses. These inputs can be used to identify the most effective set of data and analytics and help create useful applications.

The basic idea of using passive measurements from individual and collections of warfighters in order to improve situation awareness and identify blind spots is attractive. It also offers a test-bed for a variety of other important application areas such as agent assistants and future human-agent teaming scenarios. The principal challenges include implementation of the EEG sensing mechanisms in a manner that would be minimally inconvenient to the subjects; ensuring that the signal processing module can detect the signal of interest with sufficient reliability (e.g., with sufficiently high signal-to-noise ratio especially in the face of the inevitable motion artifacts); facilitating automatic or near-automatic operation in the field (i.e., without need for a human guide to focus the attention of the system when operating in the field, establishing a common view by subjects and targets of interest); developing a data and decision fusion framework for scene analysis from multiple inputs including identification and isolation of nonparticipatory players and scene-change detection (this task would involve adaptive decision fusion); and scaling (i.e., the work presented so far involved a single subject or a small group of subjects in laboratory settings, and implementation of the algorithms is required in more realistic environments and in larger scales).

The success of an HID system depends on a higher-level fusion module that would interpret the results of the detection subsystems. Devising this module is challenging because it requires a priori definition of targets (versus clutter and interference) as well as a high level of agreement between the human sensors on their classification of potential targets (what is important and what is threatening). Data

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[7] For example, see V.J. Lawhern, A.J. Solon, N.R. Waytowich, S.M. Gordon, C.P. Hung, and B.J. Lance, 2018, EEGNet: A compact convolutional network for EEG-based brain-computer interfaces, arxiv.org/abs/1611.08024.

fusion or decision fusion would be needed, with the ability to adapt (e.g., tune out a participant who is not observing the same scene that one's team members observe).

The HID project team was open to considering other inputs that could help interpret the EEG and gaze data. One potential area is collecting and leveraging the conversations between soldiers in the field as they communicate about what they are seeing and its potential importance. Several projects currently under way elsewhere in ARL are focusing on how to analyze conversations such as these, and they could potentially benefit the HID program.

Given that decision making in the field would depend on many other inputs and signals, it would also be desirable to qualify the expected contribution of the human interest detector system to scene analysis quality—that is, how inclusion of input from the human interest detector may affect the probability of detection, probability of false alarm, and the receiver operating characteristic (ROC) curve.

The potential of real-world neuroscience to disrupt current situation awareness technology is high, given that real-world neuroscience may provide measurements and human reasoning about sensed scenes that are not available at present from other sources. Realization of this potential requires overcoming technical obstacles—among them developing high-quality wearable sensing data collection systems that are robust to motion and noise. The availability of signals that are easier to collect, such as communication between soldiers, competes with this HID technology.

CYBER SCIENCE AND KINESIOLOGY

ARL's cyber science group focuses on the human aspects of cyber in support of three thrusts: training assessment, informed technology selection, and development of cyber operational plans (OPLANs). The goal of the kinesiology group is to improve the understanding of physical human performance in order to optimize soldier performance.

Accomplishments and Advancements

The cyber team has made good progress in the 2 years since their work was previously reviewed by the ARLTAB. Cyber science is getting considerable focus and funding in commercial industry and across the DoD and Services. The ARL cyber team has done a good job of finding an important research niche when most focus elsewhere is on building tools.

With its performance assessment suite for the Cyber Mission Force (CMF), ARL is tackling the challenging problem of assessing the performance of the CMF. Assessing effectiveness of these teams and their training is more challenging for this mission than for more tangible, kinetic missions.

The cyber science group has done a good job of identifying and establishing partnerships with organizations including the Persistent Cyber Training Environment, the National Guard's CyberShield exercises, USCYBERCOM, and the Cyber Center of Excellence.

Their concept of understanding operators before building tools is unlike the approach taken by most tool developers in the space. This concept for supporting insertion of automation dovetails well with ARL's larger focus on human-agent teaming while focusing on how this applies specifically to cyber.

The continued focus that the cyber team is placing on developing new behavioral measures and metrics is commendable. Throughout its work, there is thoughtful consideration in developing and integrating different measures in their attempt to understand human behavior while engaged in demanding cyber tasks. With questionnaires, eye tracking, successful cyber task completion, location tracking, and other methods, the team is continuing to make advancements that improve understanding of human-cyber behavior. Quality behavioral measures and metrics are foundational to advancing scientific progress in this field, and the cyber team is making important contributions in developing this science at the individual level and at the team level. It is not clear how this work could support ARL's objective of supporting cyber operational planning.

The kinesiology group is developing methods for objective, quantitative characterization of the ways in which soldiers move and need to be able to move in order to perform a range of tasks that could be supported by physical augmentation systems such as an exoskeleton. The current focus is close combat operations. This will allow movements to be objectively compared between conditions where soldiers are and are not wearing augmentation. The group plans to determine which kinematic variables are most informative. This quantitative approach is an important advancement over prior qualitative ways in which task performance has been evaluated. It is important to provide this type of information to exoskeleton designers so that they fully understand these important requirements of soldiers' equipment. This work can have important implications for military and civilian applications of exoskeletons. The capacity for performing quantitative assessment of effectiveness can also be applied to other means of enhancing soldier physical performance.

Of particular note is the project on team performance in a series of cybersecurity defense competitions: generalizable effects of training-type and functional role specialization, with the team actively engaging with collegiate cyber teams and collecting data. The active, deep engagement of collegiate cyber teams, as a source of input data and as test subjects for the results of other projects, is particularly creative given their skill sets and the availability challenges of operational cyber protection teams (CPTs).[8] The progress ARL is making in building relationships with the National Cyber Collegiate Defense Competition teams will serve it well as it continues this promising line of research.

Challenges and Opportunities

Being disruptive in the cyber domain overall is challenging given the level of funding spent by commercial industry and the long lead time of the government acquisition system. There appears to be a tension between ARL's stated mission of fundamental research and the push to meet the near- to mid-term requirements of the Army's cross-functional teams. The project on team performance in a series of cybersecurity defense competitions could be extended to include collection of team training history to build a more complete set of metrics that might affect team performance in addition to the individual team member training history.

The Army (and the whole of DoD) is in the uniquely challenging position of having deep and broad requirements for cyber warriors, while not having the funding to compete with industry for the most qualified individuals. Nothing suggests that this situation will change. As such, the Army needs to fill the gaps itself. The cyber science group has the opportunity to help the Army grow better cyber warriors by ensuring that the Army's training and the resulting teams are effective. ARL needs to leverage what is being done by industry as well as use open source tools for such leveraging.

To align more with ARL's human-agent teaming goal, the project on explainable AI has the opportunity to apply AI/ML to improve the quality of the knowledge base by applying feedback from the user rather than just informing the user based on an extant knowledge base. More generally, the project has an ambitious scope and needs to be tracked carefully to ensure that project milestones are met.

New projects that the kinesiology group is planning blend neuroimaging with biomechanics to understand how the body perceives constraints imposed by exoskeletons. This could lead to new training techniques for soldiers learning to work with an exoskeleton and eventually to smart exoskeletons that could adapt and respond to and even perceive the intent of the user. This is consistent with the overall goal of the Army, which is that technology needs to adapt to the user.

This research could also contribute and lead to other types of human-technology teaming, such as human-robot soldier teaming and the training of robot soldiers to perceive intent of enemy combatants.

[8] Although not within the mission of ARL, this could also represent an opportunity for the Army to recruit future CPT members.

The key challenge for the group is in the uncertainty of who or what the future soldier will be, human or robot or a blend. The group needs to continue to identify ways of supporting the physical performance of tasks that will continue to be allocated to human soldiers, and the group can play an important role in identifying those tasks at which human soldiers (with or without augmentation) will excel over robotic soldiers.

NEUROSCIENCE, TRAINING EFFECTIVENESS, AND STRONG

The role of the HS core competency research is to create individualized, adaptive technologies to augment or enhance the cognitive functions of the warfighter. Within this broader goal, the HS research portfolio includes a variety of neuroscience research programs aimed at understanding factors affecting warfighter performance in a variety of domains related to performance of the individual and the group as a collective unit. The HS core competency area comprises a team of psychologists, neuroscientists, and biomedical engineers, and their competencies include measurement and analysis of electrophysiological and behavioral signals in humans immersed in complex, real-world testing scenarios.

Accomplishments and Advancements

The group has established a unique and valuable niche for engineering advances for neurophysiological monitoring in dynamic tasks, such as ambulatory EEG and eye-gaze tracking. Specific contributions include novel algorithms for achieving accurate, reliable, and online detection of evoked response signals in the EEG while subjects are engaged in complex, operationally relevant activities. The group has also made novel contributions to the hardware and software technologies for EEG monitoring, particularly in mobile scenarios, which are prone to contamination from motion and environmental noise sources. The group has taken a rigorous approach to addressing these problems, developing a novel test-bed for isolating and eliminating sources of noise through innovative electrode and signal processing strategies.

The group has also created unique testing platforms for studying human performance in complex tasks involving teaming among groups of humans and autonomous vehicles in ecologically valid settings. These platforms are generating data sets that are unique and exceedingly rich in measuring physiological and behavioral aspects of human performance, spanning multiple time scales and modalities. In addition to supporting immediate questions, these data sets could be leveraged to support secondary analyses within and beyond ARL.

Challenges and Opportunities

The researchers do not think of themselves primarily as engineers building innovative systems, but as researchers who plan to use the systems that they are building now to expand the bounds of cognitive science, especially as it can be applied to the learning and training of teams and individuals. There are three important scientific purposes that this work might address: machine modeling as it relates to brain areas, contributions to cognitive theory as it relates to joint actions between pairs of team members (human-human or human-robot pairs) and to integration of perception with action in predictive processing, and archiving the nearly unique set of individual and team performance data that this work is and will be generating.

Machine Modeling of Human Cognition

The past 10 years have witnessed a merger of machine learning methods with the modeling of brain functions. The discussion here is limited to two efforts: adaptive control of thought—rational (ACT-R) and NENGO (a Python tool for building large-scale functional brain models).

Although ACT-R has existed since 1993, the neuro-version of ACT-R is much more recent. Carnegie Mellon University (CMU) has recently applied ACT-RN (where "N" is added for "neuro") to examine brain processes via three highly varied types of technologies: magnetoencephalography, EEG, and functional magnetic resonance imaging.[9] For magnetoencephalography, a combination of hidden semi-Markov models and multivariate pattern analysis is used to locate brief bumps in the sensor data that marked the onset of different stages of cognitive processing. For EEG, CMU developed a method that identifies on a trial-by-trial basis where brief sinusoidal peaks (i.e., bumps) are added to the ongoing electroencephalographic signal. It was proposed that these bumps mark the onset of critical cognitive stages in processing. For functional magnetic resonance imaging, the CMU researchers combined multivoxel pattern analysis to identify cognitive stages and hidden semi-Markov models to identify their durations.[10] When applied to a problem-solving task, this method identifies four distinct stages of cognitive processing—encoding, planning, solving, and responding.

A neuroengineering framework was provided to explore how cognitive processes can be implemented in a biological substrate.[11] This work has been influential, with publications in *Science*[12] and other journals.[13,14]

In addition to this group's many publications, both the ACT-RN and NENGO projects have provided tutorials at annual conferences and summer schools, and they freely share their software. HS scientists interested in developing applications for soldiers whether as individuals or as teams (human-human or human-robot) would be welcomed into these communities of researchers.

Advancing Cognitive Theory

A side effect of ignoring the cognitive modeling community may be the lack of awareness of changes in areas of research developed over the past 15 years as well as the concomitant changes in basic cognitive theory. At least two of these changes are directly relevant to ongoing HS research—joint action and predictive processing.

Joint action refers to the interactions of two individuals (human-human usually, but human-robot increasingly) at the level of eye movements, actions, and general coordination.[15,16] A joint action is an

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[9] J.R. Anderson, J.P. Borst, J.M. Fincham, A.S. Ghuman, C. Tenison, Q. and Zhang, 2018, The common time course of memory processes revealed, *Psychological Science* 29(9):1463-1474, PMID: 29991326.

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[11] T. Bekolay, J. Bergstra, E. Hunsberger, T. DeWolf, T.C. Stewart, D. Rasmussen, X. Choo, A.R. Voelker, and C. Eliasmith, 2014, NENGO: A Python tool for building large-scale functional brain models, *Frontiers in Neuroinformatics* 7, https://doi.org/10.3389/fninf.2013.00048.

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[13] T. DeWolf, T.C. Stewart, J.-J. Slotine, and C. Eliasmith, 2016, A spiking neural model of adaptive arm control, *Proceedings of the Royal Society B-Biological Sciences* 283(1843), https://doi.org/10.1098/rspb.2016.2134.

[14] T.C. Stewart, T. Bekolay, and C. Eliasmith, 2012, Learning to select actions with spiking neurons in the basal ganglia, *Frontiers in Neuroscience* 6, https://doi.org/10.3389/fnins.2012.00002.

[15] N. Sebanz and G. Knoblich, 2009, Prediction in joint action: What, when, and where, *Topics in Cognitive Science* 1(2):353-367.

event grounded by two or more agents' actions.[17] In this definition, it does not matter what the "joint" reaction or action is. It could be fish swimming together or arms swinging, but the cues are all nonverbal communication during teaming. When two people swing their arms in synchrony, the event of their swinging their arms is a joint action. Likewise, if fish are agents, then the movements of a shoal are joint actions. Well beyond fish and arms, joint action focuses on nondeliberate actions such as the coordination of eye movements when two humans work as a team on a physical task wherein the nonverbal, point-of-gaze of one human attracts the point-of-gaze of the other human without deliberate thought or conscious awareness by either team member. A critical review of the emerging action simulation theories in the wide-ranging embodied cognition and motor cognition literatures provides an integrative neuro-computational account of action simulation that links it to the neural substrate and to the components of a computational architecture that includes internal modeling, action monitoring, and inhibition mechanisms.[18]

A second and related omission is predictive processing (PP).[19,20] PP builds on a series of studies begun in the 1990s that showed that action simulation and imagery could be neurally realized by the same brain mechanisms that control the execution of overt actions. It has taken about 15 years for the implications of this work to be fully understood. Acceptance of this work has contributed to blurring the traditional separation between perceptual, cognitive, and motor domains and has resulted in assigning sensorimotor simulation a prominent role in higher cognition.

The insights of PP have been codified as internally generated sequences of structured, multineuron firing patterns forming components of goal-directed decision systems that implement a type of sampling-based inference engine that optimizes goal acquisition at multiple time scales of online choice, action control, and learning. Although much of the evidence for PP is brain-based, its implications are applicable to the external world. An excellent introduction to PP is a tutorial paper by an international group of primarily transportation researchers, which introduces PP in the context of automobile driving.[21] The mix of humans and robots, tools, and data available to HS researchers is much richer and could be leveraged into a productive line of research that furthers both basic and applied goals.

Data Archiving

The behavioral and physiological data collected by the HS researchers are considered a national treasure. HS researchers could archive those data using modern data archiving procedures. Examples of existing archives include the German Chess databases,[22] the archives of the Open Science Foundation,[23] and the archive established and endorsed by the American Psychological Association.[24]

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[16] G. Knoblich, S. Butterfill, and N. Sebanz, 2011, "Psychological Research on Joint Action: Theory and Data," in B.H. Ross, editor, *Psychology of Learning and Motivation: Advances in Research and Theory*, volume 54, Burlington, MA, Academic Press, pages 59-101.

[17] S.A. Butterfill, 2017, "Coordinating Joint Action," in *The Routledge Handbook of Collective Intentionality*, London, Routledge, pages 68-82.

[18] G. Pezzulo, M. Candidi, H. Dindo, and L. Barca, 2013, Action simulation in the human brain: Twelve questions, *New Ideas in Psychology* 31(3):270-290.

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[22] N. Vaci and M. Bilalic, 2017, Chess databases as a research vehicle in psychology: Modeling large data, *Behavior Research Methods* 49(4):1227-1240.

OVERALL QUALITY OF THE WORK

Human-Autonomy Team Interactions and Humans Understanding Autonomy

The technical quality of some of the research, observed primarily through one-on-one technical conversations with individual ARL researchers (e.g., during the poster sessions, and a select few studies presented), appeared to be high and on par with quality research being conducted at other leading research institutions and universities. In general, there is a wide variance in the quality of research being conducted.

Scientific communication at the programmatic level seems to be geared toward front-line stakeholders of the research, as opposed to the broader scientific community. A rigorous understanding of the human sciences concepts and applications being pursued, definitional fidelity, and identifying the conceptual gaps at the forefront of human-autonomy teaming was missing. At times, it was difficult to evaluate both the potential science and innovativeness in much of the research programs presented owing to these missing elements.

Much of the work on human-autonomy teaming specifically appeared to echo past research using different terminology but similar concepts, or to iterate on research coming from top laboratories in this area, rather than driving innovation in this space and asking novel questions that will shape the next decade of research in this area.

ARL researchers are ambitiously engaged in learning and applying state-of-the-art AI/ML approaches in the effort to create advances in autonomy that enable human-autonomy teaming. For some of the researchers, the AI/ML work appears to be a second language, meaning that their formal education only tangentially relates to the algorithms that need to be developed. Consequently, some of the AI/ML work is more replication of existing work than innovative research that is likely to lead to major advancements.

Autonomy Understanding Humans and Estimating Human-Autonomy Team Outcomes

Many researchers demonstrate an in-depth understanding of the unique challenges in their research. Researchers on the brain dynamics of driver-passenger communication, human-AI interactions for intelligent squad weapons, and trust in automation efforts demonstrate a broad understanding of the state of the art. However, a broad understanding of the state of the art was not uniformly demonstrated.

The research group is highly interdisciplinary, including sociologists, neuroscientists, mathematicians, psychologists, and researchers comfortable with the application of black box ML techniques. The project on human-AI interactions for intelligent squad weapons is an example of how an appropriate mix of AI and human science-focused researchers can tackle an interdisciplinary problem.

The researchers demonstrate the ability to identify the civilian research questions that can be studied. This is evidenced by the breadth of publications styles and venues, which is what would be expected of high-quality research. Publications are a mix of human factors, neuroengineering, and other area specific journals but include domain-specific publications like *American Journal of Infection Control*. Projects are an appropriate mix of low-level, single-investigator work and large-scale team efforts (e.g., the driving simulator project had issues involving integration of neuroscience hardware with data collection and synthesis). Researchers are a mix of strong experts, including experimentalists, human factors practitioners, experts in application of neuroscience techniques to human problems, and sociological research methodologists (quantitative and qualitative methods).

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[23] See COS, "About the Center for Open Science," https://osf.io, accessed May 11, 2020.

[24] See American Psychological Association, "Access to *Archives of Scientific Psychology* Data," https://www.apa.org/pubs/journals/arc/data-access, accessed May 11, 2020.

Human Interest Detection

Significant progress was made toward feasibility, but substantial challenges remain. These include robust collection of sensory information in the field, overcoming motion artifacts, and attention focusing and decision fusion architectures that have not yet been developed. The work has contributed key tools for improved EEG measurement techniques and improved signal processing tools (e.g., the convolutional neural network used in EEGNet). The work has not yet characterized fully the quality of binary target detection (the trade-off between probability of detection versus probability of false alarm and the development of the receiver operating characteristic [ROC] curve).

Cyber Science and Kinesiology

Evaluation of the technical quality of the cyber science work may be somewhat premature given that this effort is relatively new. The team established its goal as developing quality human-cyber metrics 4 years ago, and it is continuing to pursue that goal. The kinesiology group has state-of-the-art facilities, equipment, and software to support this work. The project on performance assessment suite for the cyber mission force and generalizable effects of training-type and functional role specialization appear to be on the right track to collect the data necessary to support the stated research goals. The project on explainable AI applied as a junior threat and vulnerability analyst has identified several good, authoritative sources of data to support the project, but it could have made more progress in 1.5 years. The project on participation shifts explaining degree distributions in a human communications network does not appear to be well-conceived with respect to Army-specific problems in the social network domain, nor does it appear to be doing work that advances the state of the art.

Given the time scale at which progress is made in the commercial and adversary cyber domain, it would be nearly impossible for ARL to be disruptive in this space considering the inherent time scales of research and DoD funding cycles. Most work in the cyber domain is focused on building tools and execution with less focus on evaluating the effectiveness of either.

Neuroscience, Training Effectiveness, and STRONG

Most of the research work was described as building the infrastructure required to conduct a variety of studies under conditions as close as possible to actual combat. While the group used various mathematical and ML-style modeling techniques, it seems largely unaware of the progress being made in the neuromodeling of human behavior, especially by the ACT-R and the NENGO communities. This may reflect a lack of group background in brain studies and cognitive neuroscience. Likewise, two of the most innovative approaches to integrating cognition, perception, and action are predictive processing theory and joint action, with joint action being an extension of predictive processing to the cognitive, perceptual, and action interactions between two intelligent beings. The group has access to whatever equipment it believes it needs. This access extends to custom-built nonmobile vehicles for future studies of mixed mobile teams of human and robot vehicles. The facilities and equipment are state of the art. The current research approach is not theoretical in that data are collected and analyzed but with a very task-oriented focus. This style of work is common among human factors groups in which finding a solution to a current, well-specified problem is more important than contributing to the development of theory. The main emphasis of the work was on computation and experimentation, not theory.

RECOMMENDATIONS

ARL needs to continue to focus on its long-term vision for advancing basic science research in human sciences. Its leadership needs to engage in more dialogue regarding its research strategies with its front-line researchers as well as the greater scientific community. An approach that incorporates both bottom-up and top-down approaches to science would strengthen the program and allow ARL to advance its position to the forefront of basic research.

To inform the quantitative work, ARL needs to focus its efforts on more rigorous understanding of the qualitative concepts and in rigorous qualitative analysis. The former captures the forest, and the latter grows the trees. ARL researchers need to experience the environments that its stakeholders experience firsthand, to help enrich their appreciation of the emotional and physical complexity of the work environment constraints, and to elucidate the generalizability of their potential research questions. This experience would provide the needed complexity for grounding and generating innovative science within the environment that the science is meant to impact.

Recommendation: The Army Research Laboratory (ARL) should consider formal mentoring mechanisms that can assist junior developers with designing methodologies that appropriately place work in the context of the state of the art. ARL should examine the mechanism by which individual projects are selected. ARL should ensure that individual research projects collectively contribute to research questions identified on the roadmap. ARL should select individual projects based on existing evidence that outcomes will likely contribute to the open research questions. ARL should determine the appropriate mechanism for conducting research that leverages the state of the art in both human sciences research and machine learning research.

Human-Autonomy Team Interactions and Humans Understanding Autonomy

ARL needs to continue to collaborate with universities through its state-of-art data collection facilities and through the STRONG program. Doing so would develop the top talent needed among the next generation of researchers to realize ARL's long-term research vision for advancing U.S. Army capabilities and to broaden the pool of trainees familiar with the unique challenges the Army faces. As with the ARL Open Campus Initiative, the richness of data that could be collected through ARL facilities is an inexpensive way to collaborate and if strategically planned could support several different laboratories asking the same questions from different angles to more robustly inform the research in these multifactorial environments with emergent outcomes.

It is unclear how the processes for collaboration and coordination with external researchers through the STRONG program will be measured and precisely how this program will lead to innovative advancement over incremental science. The processes through which collaboration occurs is critical. ARL needs to more clearly define the expected outcomes and to conduct a rigorous and unbiased self-study of this program to determine whether this mechanism and its processes are effective for innovative research.

Human-autonomy teaming needs to include many team phases, including mutual training, planning, execution, and after-action reviews. "Training" in the previous sentence is not used in the sense of procedures that are formally specified in another part of ARL, but rather highlights the need for most teams to develop shared understanding and expectations through shared experiences. Algorithms designed through ML based on a preconceived notion of team behavior may not lead to resilient and adaptive human-autonomy teams, so future research needs to consider how mutual adaptation of human to autonomy and vice versa leads to resilient and adaptive human-autonomy teams.

ARL needs to identify and work with traditional well-founded researchers of teamwork and newer researchers focused on this area. In general, it is important to work with experts beyond the long-established and funded experts. It is also important to identify interdisciplinary researchers who have background in the many disciplines relating to human-autonomy teaming.

The continued success of ARL and the human sciences core competency is critical to ensuring that human-autonomy teaming does not end up being solely technology centered.

Understanding the communications and interactions between human-machine agent teaming is critical for the operational success of teams and system performance. In addition, if such systems are to become disruptive, it is imperative that designers of such systems understand the various dimensions of human-machine interactions such as intent, trust in automations, and so on. Similarly, designers of such systems need to anticipate how the machine will respond to the variability in human responses. Therefore, a sustained research concentration on human-autonomy teaming is critical.

Recommendation: The Army Research Laboratory (ARL) should consider giving priority for the interaction of multiagent teaming in human sciences research efforts. Such projects should provide input (insights, understanding, data, etc.) that results in a better understanding of human-autonomy interactions.

Autonomy Understanding Humans and Estimating Human-Autonomy Team Outcomes

Many researchers demonstrate an in-depth understanding of the unique challenges in their research. Researchers on the brain dynamics of driver-passenger communication, human-AI interactions for intelligent squad weapons, and trust in automation efforts demonstrate a broad understanding of the state of the art. However, a broad understanding of the state of the art was not uniformly demonstrated.

Researchers are expanding the scope of autonomy understanding individuals to include predictions of human-autonomy team outcomes. This effort is less mature, and researchers are focused on what data to collect to evaluate team effectiveness and outcomes. Initial efforts involved looking at communication effectiveness and resulted in the creation of a tool to annotate human conversations. A study of human-to-human communication under higher cognitive workloads provided an opportunity to evaluate the usefulness of the tool. The goal is to understand how to evaluate mixed team effectiveness, possibly utilizing methods identified for evaluating individual or exclusively human team performance. The choice of this approach to measure communication effectiveness is not well motivated.

Human Interest Detection

Presentation of ARL's current HID research efforts in context is needed. ARL needs to provide past work found in the literature, including previous work in attention focusing and ARL-supported work (especially in the Cognition and Ergonomics CTA).

A framework is needed for binary target detection using the human interest measurements (probability of detection versus probability of false alarm and ROC); this framework is likely to require adaptive decision fusion.

A clear roadmap is needed, including potential dependency on related research from other programs, metrics for success, milestones, and timelines. Milestones could include 3-5 realistic test scenarios specifying how many subjects would be using the HID system in a field test, what tasks and targets will be looked at, what form factor and other wearability constraints would need to be met by the HID system, and what ROC or probability of detection/probability of false alarm performance points on the ROC curve would be achieved.

Software development has advanced at a tremendous pace over the past few years. Much of the reason for this rapid development is the increasingly common practice to employ open source software to build software platforms. Because of this rapid pace, it will be difficult for ARL to remain competitive within the software development space. ARL needs to be a member of GitHub[25] if it is not already.

Recommendation: The Army Research Laboratory (ARL) should develop a mechanism for collaboration between ARL and industry on software development. Specifically, ARL should use and develop software platforms in collaboration with open source software libraries that will enable ARL to keep up to date and to rapidly develop human interest detection (HID) software. In addition, given the difficulty of attracting top talent in the HID space, ARL should make a focused effort to attract high-quality talent through sabbaticals, postdoctoral fellowships, and workshops.

Cyber Science and Kinesiology

The cyber science group has made good progress in 2 years, including identifying areas where the Army has unique challenges. The cyber science group could continue to extend its work on individuals to teams in the areas of performance assessment and tool selection. Additionally, ARL could continue its progress in innovating and integrating new human-cyber behavioral measures and metrics, because that research is fundamental to advancing the science. The cyber science group could extend its external teaming efforts to identify and engage with Army organizations responsible for development of cyber operational plans so that its thrust in this area has a transition target. The cyber science group brings a unique skill set to the Army that could be left intact or allowed to grow to advance the science. The cyber science group possesses a skill set that could be attractive to other groups—for example, training or computer science. If that skill set were siphoned away into other groups within the Army, the human science that the group is advancing will suffer.

The kinesiology research strives to ensure that physical agents such as exoskeletons are designed based on how humans need to move so that they can team well with the warfighter. For the future work that the group envisions, studying smart exoskeletons is an interesting path to pursue. However, this research effort needs to better understand the musculoskeletal "cost" of the technology. Supporting the physical performance of tasks that will continue to be allocated to human soldiers is an important contribution of this group. The group can play an important role in identifying those tasks at which human soldiers (with or without augmentation) will excel over or be able to keep pace with robotic soldiers, and vice versa, as robotic technology advances.

Recommendation: The kinesiology researchers should consider the top-level question of what is different about kinematics for the Army rather than being pulled solely by ARL's strong focus on human-robot teaming.

Neuroscience, Training Effectiveness, and STRONG

Changes made in the personnel, organization, and structure of the HS core competency area have provided the tools and opportunities needed to make it a national laboratory in the area of cognitive science and robotics for individual human performance as well as for human teams and mixed teams of humans and robots. The funding directed to this group by the Army has enabled the researchers to build

[25] GitHub is a major open source group; see https://github.com/.

the next generation of high-technology research tools with which to study human performance in combat simulations both with and without robotic teammates.

> **Recommendation: The human sciences core competency area should build on its strengths by acquiring expertise in those areas of cognitive science that focus on joint actions among individual intelligent entities (i.e., human-human and human-robot). Likewise, the Army Research Laboratory (ARL) should adopt a research strategy that embraces the findings of predictive processing, with particular attention to the dynamics of military operations.**

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Materials and Manufacturing Sciences

The Panel on Materials and Manufacturing Sciences at the Army Research Laboratory (ARL) conducted its review of selected research and development (R&D) projects of the ARL materials and manufacturing sciences research core competency during a virtual meeting on May 26-29, 2020. The research areas reviewed were optical science and photonics, electronics and optoelectronics, and energy science.

ARL's materials sciences span the spectrum of technology maturity and address Army applications, working from the state of the art to the art of the possible. Army's vision for multi-domain operations (MDO) is that the Army of 2035 and beyond uses advanced technologies to achieve overmatch across a wide spectrum of domains and environments. The desired end state of the materials and manufacturing sciences core competency is to leverage the broad materials community to produce materials that enable the materiel to give soldiers unprecedented overmatch across the increasingly dynamic, complex, multi-domain battlefield of the future. Materials research efforts and expertise are spread throughout the ARL enterprise. As the ensemble of the materials discipline and capabilities, the area of materials and manufacturing sciences is one of ARL's primary core technical competencies. In the larger context, the mission of ARL, as the U.S. Army's corporate laboratory, is to operationalize science for transformational overmatch.

The specific optical sciences and photonics programs reviewed were integrated photonics, quantum information sciences (quantum optics), sensor protection, and advanced solid-state lasers. Each of these research priorities is linked to well-articulated Army needs. For example, the quantum information sciences program is motivated by the potential to move Army optical systems beyond classical capabilities, and the necessity to control or eliminate technical surprise that might otherwise result from the continuing aggressive research efforts in the areas of quantum optics or solid-state lasers of other nations. Another notable priority—assured positioning, navigation, and timing (A-PNT)—suggests the necessity to develop atomic clocks and other frequency and time standards with significantly improved properties.

The research themes of the electronics and optoelectronics areas were diamond electronics, microdevices, materials-driven antenna design, optical power devices, emerging materials, and radio frequency (RF) and digital electronics. Again, the evaluated projects were motivated by Army needs—two examples are emerging materials being explored as a means to increase information and data assessment in the field; and materials-driven antenna design, which addresses the Army's expanding communications size, weight, and power as well as cost (SWaP-C) needs.

Six areas of research falling under the umbrella of energy science were reviewed: (1) artificial muscle, (2) energy harvesting for fuel flexibility, (3) thermal science, (4) energy storage and batteries, (5) alternative power, and (6) nuclide power. This research falls within the general science and technology (S&T) areas of energy harvesting, conversion, storage, and delivery and in most cases is linked to Army needs. For example, the team working on aqueous lithium-ion battery (LIB) materials and systems is making exceptional advancements in the S&T of electrical energy storage with lithium-ion batteries.

ARL's work in preparing for the review was particularly noteworthy given the unknowns associated with this first effort at a virtual review. Overall, the researchers and the management are of high caliber and deserve credit.

OPTICAL SCIENCES AND PHOTONICS

The reviewed research themes of the optical sciences and photonics area were integrated photonics, quantum information sciences (quantum optics), sensor protection, and advanced solid-state lasers.

Each of these research priorities is linked to well-articulated Army needs. For example, the quantum information sciences program is motivated by the potential to move Army optical systems "beyond classical capabilities," and the necessity to control or eliminate technical surprise that might otherwise result from the continuing aggressive research efforts in the areas of quantum optics or solid-state lasers of other nations. Another notable priority—assured positioning, navigation, and timing (A-PNT)—suggests the necessity to develop atomic clocks and other frequency and time standards with significantly improved properties.

Accomplishments and Advancements

The panel was impressed with the prominence of early-career scientists in the presentations and the research groups for each of the four themes. Furthermore, the connections between individual projects within each theme were, in general, expressed clearly and the logic was compelling. Another commendable aspect of all of the research themes is that of collaborations. Collaborations throughout the optical sciences and photonics program were diverse and strong, to the extent that the research advances emanating from these partnerships demonstrates that "the whole is greater than the sum of the parts." That is, the time and effort invested by ARL researchers in developing these collaborations have resulted in a substantial return to the ARL research effort.

The fundamental research conducted in the quantum information sciences group is especially impressive and the demonstration of the first communications receiver based on Rydberg atoms is a major milestone of which all of ARL can be proud. The successful effort to store information in spin waves is also promising and a credit to this research team. The advanced solid-state lasers group continues to be one of the "crown jewels" for ARL by driving infrared laser technology with the recent achievement of lasing at 3 microns in new, low-phonon energy hosts such as barium fluoride and yttrium lithium fluoride. The sensor protection scientific team is commended for the clever iridium chemistry that is being pursued to develop broadband reverse saturable absorption materials and the guided-mode resonance (GMR) filters. Among the impressive accomplishments of the integrated photonics research team is the dramatic improvement in the performance of optical frequency combs and the successful demonstration of electrically steerable phased arrays.

Impressive collaborations have been established between each research group in the optical sciences and photonics program and key external research groups or commercial fabrication facilities such as Fisk University and AIM Photonics, respectively. Such collaborations effectively multiply the impact of ARL programs by bringing expertise and optoelectronic fabrication or crystal growth capability not available in-house. Such collaborations also infuse new concepts into ARL programs, thereby avoiding the dangers of "group think" that inevitably and adversely affect programs that are more insular. The management of the optical sciences and photonics program is commended for the cross-linking of its research efforts, leading to interconnectedness of its research programs. This approach needs to be maintained and, most importantly, the efforts continued to aggressively pursue new areas that have the potential to reap enormous benefits for Army programs. The quantum information sciences effort, which did not exist as recently as a few years ago, is an excellent example of an initiative into research areas that might be viewed as risky by many but that has already paid handsome dividends. The advanced solid-state lasers program has been a key part of the ARL research portfolio for decades, and it continues to be the leader in this country in solid-state laser development, and particularly in the critical 3-5 μm region that is critical to the Army. The optical sciences and photonics program at ARL has demonstrated the ability to balance the protection and support of strong existing programs with a willingness to pursue promising new fields in which ARL has not worked previously. For this achievement, the leadership is commended.

Integrated Photonics

The motivation undergirding all of the research presented in the integrated photonics area appears to be twofold: the development of new optical materials and devices having capability not available previously and yet closely tied to Army applications; and interfacing micro- and nano-electronics to optical devices and arrays so as to realize a new generation of optoelectronic systems providing control of optical systems at electronic speeds. With regard to the former, presentation included the development of precision microwave source for use as a clock/frequency standard that was based on micro-resonator optical frequency combs in which the phase noise has been suppressed by use of a self-referencing circuitry more than 10 dB better than a state-of-the-art Wenzel "Golden" Quartz resonator within performance of phase noise of −130 dBc/Hz at 1 kHz for a 10 GHz signal. Frequency combs and atomic clocks will undoubtedly be the workhorses as frequency standards in future Army communications systems, and, for the frequency comb in particular, the magnitude of the phase noise determines its frequency stability. In coordination with the precision microwave source, a new environmentally stable resonator is being developed. Research was facilitated by a collaboration of ARL with California Institute of Technology (Cal Tech) and University of Maryland, Baltimore, Campus—both leaders in the field of optical microresonators. This partnership is likely to yield new resonators that are designed specifically for Army communications applications.

An example of the development of new optical/infrared materials for Army needs is the long-wave infrared (LWIR) window research effort. By combining the properties of nanomaterials with a "host" material, promising results have been obtained in the pursuit of LWIR materials that do not suffer from the drawbacks of long-standing (conventional) materials such as zinc-selenide.

A significant, well-knit R&D effort devoted to the integration of electronic and photonic devices and systems was also presented. An optical beam-former designed for electronic warfare (EW) applications was described. Operating in the telecommunications band (1,300-1,600 nm), an RF phased array beam-former technology will be based on a true time delay splitter that uses a unique slow-light phenomena for the elongated delays necessary. The resonator is based on an indium tin oxide (ITO) epsilon-near-zero (ENZ) metamaterial that has been perfected internally to ARL. The custom air-core ITO-ENZ resonators are being fabricated in ARL's cleanroom facility. Combination of these elements will lead to a precision, long-hold-over optical clock for positioning, navigation, and timing applications. Slow-light simulations of the resonator have been performed, and the ARL team is working closely with AIM Photonics of Albany, New York, to fabricate the splitter and delay structures for use with an RF demonstration platform. ARL has participated in eight fabrication "runs" that were conducted to date at the AIM foundry, and ARL staff are working remotely with the AIM fabrication facility on a continuing basis. This level of interaction is crucial to the success of the effort.

In research efforts to develop optical phased arrays, ARL is exploring several different scanning and control architectures, with edge and vertical scanning having been achieved to date with a maximum deflection of 11 degrees for single beams. In the electronic/photonic integrated circuit (E-PIC) program, ARL is exploring the AIM foundry's ability to collocate electronic and photonics components specifically designed for AIM's process design kit. These results are encouraging and suggest that the capability for electronic steering of infrared laser beam arrays is achievable in the near term. The development of E-PIC chips is in partnership with AIM Photonics and has demonstrated numerous passive and some active electronic elements. The goal of this effort is to integrate transistors, capacitors, and other electronic components directly onto photonic integrated circuits (PICs), thus enabling both electronic processing and photonic functionality on the same chip.

Another R&D effort draws on the PIC sensing element and a photonic sensor array platform technology under development at ARL to realize wearable biosensors for warfighter health and sensor monitoring. The technology described combines a PIC sensor array with a microfluidic chamber in order to obtain a lightweight, yet sensitive, biomolecular sensor. Achieving the necessary sensitivity in a low-cost and lightweight sensor is a challenge. It was solved with an on-chip Mach-Zehnder interferometer. The shift of the interferometer's spectral modes and alterations in the free-spectral range (FSR), in particular, results in extraordinary sensitivity that makes this technological approach a practical, fieldable solution.

This is a strong program. The emphasis on interlocking optical/electronic devices or systems, which can be regarded as separable "platforms," is a wise approach because it allows small teams to focus on a particular optoelectronic functionality. At the same time, however, the individual teams are in close communication with all other teams, and, in some cases, individual researchers are members of two or more teams. In addition, the collaborations with multiple experts and organizations with unique capabilities—such as the ARL Biotechnology branch, CCDC Chemical Biological Center, Cal Tech, AIM Photonics, and Naval Research Laboratory (NRL)—are definitely assets to this R&D effort. Insular research efforts invariably "reinvent the wheel," but the integrated photonics effort at ARL appears to be able to move more quickly because of the balance of internal and external expertise. The quality of the researchers is impressive.

Quantum Information Science

Quantum information science (QIS) is currently an extremely active area of research, with many facets that extend beyond physics into other disciplines such as computer science and mathematics. Research on quantum materials and devices is central to the development of fundamental scientific understanding as well as for technological applications. The focus at ARL is appropriately on aspects of quantum materials issues that are particularly relevant or even unique to Army needs or that draw on unique Army resources and facilities. This allows the research to have an impact even in a very large and competitive field. This effort is leveraged by outside collaborations, most notably through the Quantum Technology Institute at the University of Maryland, College Park, as discussed further below. In addition, ARL QIS experts act as a source of information and advice for non-expert decision makers on what is practical and what is hype in the development of technologies such as sensors, precision navigation technologies, and distributed-entanglement secure communications systems. This role is especially important, because in most cases there is a very long time frame and considerable investment to get these projects to applications.

The promise of neutral Rydberg atom arrays for quantum information was recently highlighted in the literature—for example, in a May 2020 *Nature Physics News and Views* article. While most schemes being pursued in Europe and China require fast routing of single photons, ARL has accomplished spin wave multiplexing with a one million cold atom ensemble that currently stores 10 spin waves but, in principle, could store up to 1,000 by multiplexing via dynamic classical dressing beams while informational photons emit into a TEM00 optical cavity mode.[1] The significance of this contribution is highlighted by publication in *Physical Review Letters* featured as a "Physics Synopsis" in December 2019.

[1] The TEM00 mode is the lowest-order transverse mode. It has the lowest threshold, smallest beam waist and divergence, and it contains no nodes in the output beam transverse intensity distribution.

The work on the Rydberg atom complements long-time-frame research on quantum entanglement physics with an immediate-term project on Rydberg atom-based electric field sensor and communications, carried out by the same team. This as an excellent strategy and a significant accomplishment in its own right. Indeed, the success of this work has attracted a lot of attention. The operating principle of this receiver/antenna relies on the large polarizability and dipole moments in this regime, with unique features that distinguish it from established technologies, including the small subwavelength size, no absorption loss of radiation, and optical readout. Further, the same device can operate over a wide range of frequencies, from DC to THz, and the receiver can act as its own antenna. Work is ongoing to improve sensitivity and bandwidth.

ARL researchers are pursuing two different avenues to achieving distributed entanglement by manipulation of photons via controlled light-matter interactions in fibers. In a project using trapped $^{171}Yb^{+}$ ions as single ion qubits, progress is being made in the modeling and implementation of cavity-mediated ion-photon interactions with the goal being to achieve distributed entanglement over standard telecommunications optical fiber. In a separate project involving partnership with the Joint Quantum Institute at the University of Maryland, a 1D optical nanofiber is being explored as an efficient interface to cold atoms, with the mediation of ^{87}Rb atom-atom interactions through exchange of evanescent photons via an optical nanofiber mode. The observation of super-radiance of a few atoms separated by hundreds of resonant wavelengths was reported in a well-cited 2017 *Nature Communications* paper. Ongoing investigation includes optomechanical effects in the nanofibers, especially those that result in the loss of trapped atoms, limiting performance.

A project focusing on the development of nonlinear photonic devices for quantum devices is a relatively new effort, just getting under way, and at this stage is primarily theoretical. It directly addresses Army-specific needs for portable solid-state devices that work at room temperature, but with a long-time frame to practical devices. As such, it is an appropriate part of the strategic mix for balancing the risks and rewards of research in this area.

The project pursuing solid-state defect spin cubits is playing catch-up with a relatively established field—for example, defect spin qubits in silicon carbide have been studied since at least 2011. The team is well qualified, and the project is moving fast. The microscope for characterization of the defect represents a focused effort showing good progress.

Last, the partnership with the Quantum Technology Institute at the University of Maryland promotes strong connections with the academic QIS community through interaction with five university laboratories in atomic, solid-state, and optical physics. It broadens the perspective of researchers at ARL, and motivates and steers academic research toward Army-relevant problems, where appropriate. It also provides for access to specific research capabilities complementing those at ARL, and most important, offers interaction with graduate students and postdoctoral researchers who could potentially be recruited to work at ARL.

Overall, the mix of projects presented was impressive, and ARL's strategy for developing its presence in this very active and fast-moving field is effective. There is significant overlap and interaction between certain projects through joint participation of individual researchers which promotes rapid progress as well as visibility in the larger quantum information materials community.

Sensor Protection

A primary goal of sensor protection encompasses the foundational research of material interaction with high-intensity laser beams of different pulse widths (fs, ps, ns, and CW) and wavelengths (visible, SWIR, MWIR, LWIR) to determine the vulnerability of Army platforms, and provide protection against threat lasers. Sensor protection involves extensive materials characterization and modeling to understand nonlinear optical phenomena in specially designed and engineered organic and inorganic materials. Several important parameters of material and device design include time response, triggering mechanisms, and operating wavelength region. As a forward-looking technology, metamaterials science is employed as a paradigm to extend sensor protection capabilities beyond the confines of more conventional material solutions. There is an ongoing search for nonlinear optical materials and components that are activated by high energy or laser intensity, and only activate when a system is exposed to a threat laser. The sensor protection presentations encompassed these guiding principles.

Six posters were presented that formed a coherent set of projects that support the overall goal of sensor protection with numerous members taking part is several projects. The first three posters discussed the impact of continuous wave (CW) kW level 1-micron lasers and high-intensity fs lasers and the laser-matter interaction of materials of interest to the Army. The fourth poster discussed the development of tunable micro-engineered metamaterials designed to serve as optical notch filters in the LWIR region from 8 to 12 microns. The final two posters discussed the development and characterization of transition metal chromophores and their unique ground and excited state properties that result in reverse saturable absorption (RSA) and two-photon absorption (2PA), with the goal of providing sensor protection. The entire poster session was impressive and well received. For example, the sensor protection scientific team is commended for the clever iridium chemistry that is being pursued to develop broadband reverse saturable absorption materials and the GMR filters.

High-Power CW Damage Measurements and Protection of Optical Components

Most of the work around the country regarding laser-induced damage of IR optics has focused on pulsed laser damage. ARL is potentially the only research group investigating the CW laser-induced damage threshold of IR optics at 1 micron using 1.5 kW and 10 kW lasers. These researchers are also investigating high-reflecting metastructures to increase the damage threshold and increase the laser acceptance angle. This research is designed to determine the resiliency of this IR optics against 1-micron radiation and to make recommendations as to the suitability of specific optics in any next generation combat vehicle system. Given the unfortunate prevalence of the use of high-power, CW 0.5-micron—that is, green—laser pointers to blind airline pilots and police officers, frequency doubling these high-power 1-micron lasers to 0.5 microns will be straightforward to investigate materials for eye protection.

Characterizing Ultrashort Pulse Laser Filamentation in Optical Materials

Using NIR and SWIR ultrashort pulse lasers, measurements of the threshold pulse energy for filamentation and supercontinuum generation in relevant optical media is being performed. The Army is interested in characterizing these effects to develop unique applications that exploit such extreme nonlinear optical effects as well as to identify areas for protection to aid the service member. A goal is to determine how these nonlinear effects scale with laser power and wavelengths as long as 10 microns. Simulations are used to design experiments, and experimental results check the simulations, resulting in enhanced models of ultrashort pulse laser filamentation. The propagation of ultrashort pulses through nonlinear media produces a wide array of interesting optical effects.

Mid-Infrared n_2 Characterization in Infrared Transmitting Materials

Over the past few years, MWIR laser propagation, primarily in the 3-5 μm regime, has garnered a great deal of interest owing to high transmission in the atmosphere. MWIR ps and fs Z-scan measurements determined nonlinear refraction, n_2, and two-photon absorption (2PA, α_2) coefficients of optical materials of interest to the Army. This group was able to model the high-harmonic and supercontinuum generation they observed using second-, third-, and fourth-order nonlinearities. One of the parameters that determines the onset of filamentation is nonlinear refraction. This parameter has been investigated extensively over several decades in a multitude of materials, primarily in the visible and

SWIR spectral regimes, but very few efforts have been conducted in the MWIR region owing to the lack of capable ultrashort pulse sources. ARL is developing a unique capability for ultrashort pulse MWIR nonlinear characterization in order to determine the n_2 of Army-relevant materials as well as experimentally investigate laser-matter interactions in the visible, SWIR, MWIR, and LWIR regimes by acquiring high-energy ultrashort pulse sources with tunable frequency conversion into the MWIR and LWIR spectral regions. There is the possibility of initiating a CRADA with Ohio State University to study other effects from ultrashort pulses such as damage in Army-relevant materials.

LWIR Tunable Notch Filter Using Metamaterials

The absence of tunable notch filters in the LWIR region from 8 to12 microns is being addressed by the development of novel micro-engineered metamaterials based on a subwavelength grating on top of a Ge/ZnSe planar waveguide. These notch filters are based on the GMR effect in dielectric materials, pioneered at the University of Texas, Arlington. At present, Ge/ZnSe appears to be the only materials combination that produces a tunable filter in this spectral range. The transmission experiments were performed with a tunable quantum cascade laser system, resulting in very good agreement between experiment and simulation. Looking toward the future, ARL has started a new cooperative agreement with the University of Texas, Austin, and initiated a collaboration with the National Institute of Standards and Technology (NIST) to use their excellent cleanroom facility and expertise. These appear to be the only tunable notch filters in the LWIR from 8 to12 microns.

ARL Development of Reverse Saturable Absorption Materials Through Multi-University Collaborations

Reverse saturable absorption (RSA) is a nonlinear optical process that occurs when a material absorbs light more strongly in its excited state as compared to that of its ground state. This is in direct contrast to saturable absorbers (SAs) used in laser cavities to mode lock or Q-switch, which become more transparent—that is, bleach—under high irradiation. ARL seeks RSA materials that function across various wavelength regimes and time scales, and has robust in-house synthetic and photophysical characterization efforts for the development of RSA materials. Transition metal chromophores containing ruthenium and iridium metal centers and their unique ground and excited state properties have resulted in RSA and 2PA providing sensor protection. ARL utilizes state-of-the-art organic synthesis techniques to develop new RSA materials as well as excellent spectroscopy instrumentation for nonlinear optical characterization. In addition to ARL's robust in-house synthetic efforts and photophysical characterization, this team initiated several cross-functional multi-university cooperative agreements to augment its capabilities with University of Central Florida, North Carolina State University (NCSU), University of Buffalo (UB), University of Houston (UH), and University of New Mexico (UNM). Looking forward, this group has been funded for a second year of cooperative agreements with NCSU, UB, UH, and UNM. There is also a collaboration with the U.S. Military Academy, West Point, chemistry faculty and cadets, as well as ARL summer student researchers for increased synthetic throughput.

Synthesis and Characterization of Novel, Broadband Nonlinear-Absorbing Chromophores

Iridium-based transition metal chromophores have resulted in RSA signatures as demonstrated by open-aperture, picosecond Z-scan measurements. These transition metal chromophores have a highly modular architecture, which is adaptable to microwave-assisted synthesis, and utilizes relatively inexpensive starting materials. One major advantage of these chromophores is that they can be synthesized in a microwave reactor that greatly reduces the production time to about 1 hour instead of hours to days.

Advanced Solid-State Lasers

Mid-IR laser development constituted four short poster presentations. The focus of this research team is on new materials as well as new strategies for implementing compact, fieldable lasers operating in the atmospheric transmission window at about 3 to 5 microns. Overall, this program is a well-thought-out and integrated as well as innovative effort. This work is unique, is of high quality, is well integrated with Army needs, and has the potential for impact well beyond the needs of the U.S. Army.

The group has dedicated significant effort into developing a platform for experimentally evaluating new laser materials, including the ability to measure the thermal conductivity, spectroscopy, excited state lifetimes, and dynamics of these materials. In combination with materials growers—with a strong collaboration with Fisk University—this group has identified new BaF_2-host candidate laser materials and demonstrated their basic potential as a direct diode-pumped laser material. Other host crystals, specifically consisting of heavy-element materials combinations that exhibit low phonon frequencies to suppress quenching of the laser transition, are in-house ready for this evaluation. Mid-IR lasers have seen an upswelling of interest in recent years. In the field of laser science as a whole, entire eras of innovation can be identified by the discovery and development of a single new laser material. The ARL effort is unique and is thus a national resource. A review of the literature in the area of new laser materials makes this apparent, because no other domestic efforts in developing these BaF2-based materials could be identified. Moreover, there is no other fully domestic effort in both growing and characterizing laser crystals. It is noted that the Fisk University group has in the past been primarily focused on scintillator materials, and the ARL group was instrumental in encouraging this group to broaden the scope of its crystal growing.

The researchers within this group uniformly exhibited a good grasp of their research, as well as how their work integrates into the overall effort, and how their work compares with outside research as well as alternative approaches such as nonlinear parametric generation of mid-IR. They are also exploring novel approaches for implementation of these mid-IR laser materials, such as the concept that laser performance in the mid-IR can be enhanced through simultaneous or sequential lasing at several wavelengths as a means of mitigating the quantum defect and transporting heat from the laser material. Continued development of these concepts is needed to the point where the utility of this approach (or lack of utility) becomes clear.

Challenges and Opportunities

Integrated Photonics

The optical frequency comb research could aggressively explore and possibly developed in-house resonators beyond those available from Cal Tech. Although the latter are leaders worldwide in performance, their design is not necessarily optimized for Army applications. The design and fabricate PICs and E-PICs with AIM Photonics is a productive relationship, but the number of device fabrication “runs” is limited because ARL is the sole customer of this facility. It is, therefore, advisable to design chips that simultaneously test as many optical/electronic devices and subsystem designs as possible at one time to optimize the rate of progress toward deployable chips and systems. The group needs to explore working with additional companies with experience in IR materials.

Quantum Information Science

From the device aspect, this is a long-term project, and a number of questions will have to be addressed, including the following: Can it operate directly at telecommunications wavelengths or will it need a converter interface? How does this scheme perform relative to other candidate quantum memory schemes, and which limitations are intrinsic, and can be overcome? Moreover, this effort can benefit from a greater incorporation of theory and computation.

As the project pursuing solid-state defect spin cubits advances, there could be an increased focus on how to engineer the defects. There may be some opportunity for the silicon carbide (SiC) reactor to benefit from expertise and facilities at NRL's Advanced Silicon Carbide Epitaxial Research Laboratory.

Advanced Solid-State Lasers

The setup for measuring the thermal conductivity of various laser materials as a function of temperature is clearly a workhorse characterization setup with extensive and useful data presented. The group could explore expanding this experiment to include other measurements critical to evaluating laser operation. For thermal lensing, the variation in the index of refraction with temperature dn/dT, and the coefficient of thermal expansion a(T) both also contribute to modeling of thermal lensing in laser materials. For some applications, the nonlinear index n_2 is also important. Furthermore, characterization of temperature-dependent excited-state lifetimes yields important insight into relaxation pathways. Not everything can be done in one setup, and some measurements are easier than others. However, the ARL group is in an excellent position to raise its visibility as the "go to" group for materials developers seeking a laser materials characterization capability in the United States, which would prove to be of considerable benefit to both the ARL and U.S. laser efforts.

Although no one would dispute that direct experimental characterization of laser materials will always be necessary, a major thrust in computational materials science at present is in the materials genome—that is, developing sufficient computational fidelity on applications-relevant materials properties to guide experimental efforts. This endeavor is still far from mature, and by virtue of funding sources is driven primarily by the energy materials area. However, many of the same materials properties—optical and photoabsorption characteristics as well the feasibility of fabrication—are identical to laser materials needs. Other characteristics, such as dopant and host properties, may be different. As a leading group in the development of new materials, ARL needs to keep abreast of these efforts and, at an appropriate time, open a dialogue with groups in computational materials science that may advance the identification of new candidate materials.

Demonstrations of mid-IR lasers in rare-earth doped, low phonon energy materials such as Er:BaF2 were presented. Demonstration of lasing in a new material is an important milestone. The pump brightness requirements—provided in this experiment by a flashlamp-pumped laser—are not practical for direct diode pumping in the short term. Nevertheless, it is worthwhile to consider continuing to pursue a viable laser architecture, such as pumping by fiber lasers, as an intermediate technology demonstrator. These developments could well be of interest to scientific users outside of directed energy applications and may well lead to alternative approaches and architectures that become viable for Army applications in the longer term.

The group is exclusively focused on MIR laser materials operating within atmospheric transmission bands, for obvious reasons. Particular emphasis is being placed on lasers operating at 3 microns, which undoubtedly will be of considerable value for several Army platforms. However, it is worthwhile to broaden the wavelength region of interest. For example, lasers at about 2 microns will allow for the use of a broader range of nonlinear parametric down-conversion crystals for the 3-5 micron range.

More broadly, this program's Army-specific emphasis is too strong. Direct relevance for Army applications needs to be vigorously pursued, but also need not overshadow the broader realization that laser technology has proven to be a pervasive driver of S&T over the past half century. Laser technologies developed decades ago are now key enablers for many of the quantum science, energy, sensor protection, and materials technologies discussed elsewhere in this report. Technologies that make new regions of the spectrum accessible to coherent light will open new possibilities and new capabilities. National security, prosperity, and preeminence are all inextricably linked to mastery and control of every region of the electromagnetic spectrum.

ELECTRONICS AND OPTOELECTRONICS

The research themes of the electronics and optoelectronics areas are diamond electronics, microdevices, materials-driven antenna design, optical power devices, emerging materials, and RF and digital electronics.

Overall, the research projects in the electronics and optoelectronics area were of high quality and comparable to other first-class research organizations. The projects evaluated were well thought out and motivated by Army needs—two examples are emerging materials that are being explored as a means to increase information and data assessment in the field; and materials-driven antenna design that will address the Army's expanding communications and size, weight, and power as well as cost (SWaP-C) needs. There was a good mix of exciting high-risk projects and those that are in support of Army near-term applications.

Accomplishments and Advancements

Diamond Electronics

The Army has significant need for efficient, high-power electronics. Diamond offers potential advantages over the current standard of GaN-based devices owing to its higher thermal conductivity. The effort is currently focused on improving device performance by introducing transition metal oxides or boron nitride to stabilize the diamond surface. The target power metric of 50 W/mm has been identified as necessary for this technology to supplant the current state-of-the-art GaN.

The scientific quality of the work is excellent and makes a significant contribution to the field. The device fabrication and characterization facilities are well suited to development of a robust technology, and the expertise of the researchers is well matched to the needs of the program. Device and material modeling expertise seems to be well integrated with the processing program. There are strong collaborations with vendors and university researchers. The group has achieved state-of-the-art direct current (DC) characteristics utilizing solid oxide cap layers.

Microdevices

This poster session concentrated on making new devices useful to the Army using ARL materials capabilities. Piezoelectrics materials are an ARL strength. ARL has a Cooperative Research and Development Agreement (CRADA) with the Kurt J. Lesker Company, an organization well known for depositing thin films using atomic layer epitaxy. ARL and Lesker collaboratively deposited piezoelectrics for three-dimensional (3D) piezo-microelectromechanical system (MEMS); this is a unique and potentially important accomplishment. These studies compare very favorably with those at Penn State University and NCSU.

Materials-Driven Antenna Design

This topic area addresses the need for advanced antennae design of low profile using various materials and methods, including additive manufacturing. This area is of broad application to the Army, including communications and SWaP-C considerations. Three projects presented were (1) design, production, and 3D printing of composite filament materials for tunable dielectric performance; (2) metaferrite-based ultralow profile antennas; and (3) control of magnetic flake geometry and orientation in thin films to tailor properties. As such, these works address materials development, manufacturing and processing advances, and performance demonstration.

Significant accomplishments were reported in the development of metaferrite materials for ultra-low-profile antennas and printable filaments. The metaferrite materials are transitioning from materials development to application, especially notable for collaboration with an industrial partner—Lockheed Martin—and these antennas are in testing. The technical quality of this work is high and the transition from materials to device is lauded.

Optical and Power Devices

This poster session highlighted the development of two important device types for the Army—the improvement and standardization of high-voltage power devices, and the creation of UV emitters and detectors for covert communications and sensing. All the work is of high technical quality comparable to the best peer laboratories.

The work on developing SiC and AlGaN devices is advanced, well thought out, and broad enough to have a chance of success even though doping such large bandgap materials has historically proved difficult.

Emerging Materials

The emerging materials poster session covered approaches to two applications spaces—IR devices and low-power electronics. IR devices have long been an area of strength for ARL. Low-power electronics are an emerging need for the Army as the continued drive to increase information and data assessment in the field drives package sizes to unsupportable dimensions. All of the work reported is of high quality and shows good integration of modeling and experiment.

The Semiconductor Modeling Center is an excellent partnership that leverages expertise from multiple institutions. Although currently focused on IR devices, it has the potential to expand to a variety of other device technologies.

Novel spintronic heterostructures (Al/InAsSb), topological insulators (Alpha-Sn), and two-dimensional (2D) materials (HfS) are being explored for use in low-power or spintronic devices. Some of this work appears to leverage existing in-house capability for synthesis of antimonide materials for application to new device needs. The Alpha-Sn work, which had applications far in the future, seems like a materials capability looking for an application. The targeted approaches are truly emergent and thus less mature than the IR work, but show promise based on early results and calculations.

RF and Digital Electronics

This topic area centers on building electronic devices to demonstrate the impact of near-future semiconductor technologies and to protect a competitive electronics supply chain. Success will meet the needs of the Army that cannot be met from commercial vendors. Three posters were presented, covering the following topics: (1) development of a frequency multiplier in place of a mixer to provide electronics that operate over ultra-wideband; (2) creation of hardware architecture to run a reconfigurable neural network to enable real-time data processing; and (3) protection of integrated circuits on-demand printing of dielectric materials, with the ability to tune properties and performance.

The ultimate goals of developing specific electronics supply and protecting them are timely and will have high impact, and the research topics addressed have identified areas in which significant advances are needed to realize overmatch for the safety and security of the Army. In general, these projects are in relatively nascent stages, with preliminary effort in the broadband transmitter architectures showing the furthest progress.

The novel broadband transmitter architecture has shown important successes using two different approaches to access ultra-broadband with high precision. This has resulted in multiple patents and conference proceedings.

Challenges and Opportunities

Diamond Electronics

Issues with thermal and device stability as well as leakage at small gate lengths are important challenges to address; thus, the plan going forward to focus more attention on the area of stability is certainly warranted. In order to enhance ultimate success, ARL needs to bring additional capability in-house in the area of diamond surface cleaning and/or diamond epitaxial growth. In-house epitaxial growth would substantially increase the probability of success. Additionally, the material modeling efforts needs to focus on improving reliability for a particular heterostructure in order to accelerate progress on improving ultimate circuit reliability.

Microdevices

The applications chosen, RF filters, microelectromechnical systems (MEMS), and integrated optics, are of interest to the Army, but the advantage of these material approaches on devices needs to be demonstrated.

Hybrid manufacturing using ARL's varied material capabilities could produce some new and useful packaging for the Army.

Computational origami is a new and unusual technique for forming complex 3D structures in metal. The technique has been proven and well demonstrated, it now needs to be applied to a useful structure and tested to see how it compares to approaches that are more conventional.

Materials-Driven Antenna Design

Given the maturity and relatively high cost of the antennas from metaferrite materials, materials development for lower cost is a good future direction. The printing of composite filaments for dielectric materials with variable properties is rapidly maturing, and further work on demonstrating utility is needed. The project centering on composite magnetic materials with low loss is in a nascent stage relative to the others. Here, while simulation results are promising, further testing and experience are needed. In addition to design and fabrication, ARL needs to do computer simulation performance modeling.

Optical and Power Devices

SiC power devices are now very mature and robust, in part owing to the past work of ARL. While these devices meet commercial standards, they may not be adequate for military applications. ARL's work on fundamental calculations of material and device properties and investigations of failure mechanisms by the military device suppliers are needed. In addition, it is important to create military specifications standards for future purchases.

The success of the AlGaN work would be enhanced by having a metalorganic chemical vapor deposition growth capability in-house.

The research on developing SrTeSe-based devices is high risk but with significant potential. This work has the benefit of in-house material support, which will improve the chances of success.

Emerging Materials

Additional benchmarking on all the candidate materials presented would be helpful, as it was not clear how the results compare with other candidate materials being explored at other institutions.

ARL needs to expand the Semiconductor Modeling Center to include GaN, SiC, and diamond because these are materials systems of great interest to the Army. In addition, ARL needs to consider developing clear metrics to assess the viability of the new materials systems so that timely decisions can be made regarding the contraction or expansion of the program.

RF and Digital Electronics

There are many opportunities to validate the approaches proposed prior to significant investment of time, energy, and money, and further to determine who would provide such validation. As presented, the performance metrics expected and needed for further investment have not been defined, with an opportunity to establish go/no-go points. A challenge is also presented in the relatively limited approaches to address each project; this introduces the concern that industry and commercial vendors could meet or surpass any successes within the same time frame.

In development of hardware for neural network and protection of integrated circuits, niche applications have been identified, and would benefit from being put into context of current state-of-the art and competitor approaches for validation and development of go/no-go gates.

Researchers need to identify routes for validation of their work as soon as possible, as well as to identify technical gates to identify the performance metrics needed for continuation of the work. They also need to expand the scope of the work to increase the options for success. As presented, these works are relatively narrow, and no contingency plans or varied approaches were presented. Moreover, ARL needs to address hardening systems against electromagnetic pulse destruction.

ENERGY SCIENCE

Six areas of research falling under the umbrella of energy science were reviewed: (1) artificial muscle, (2) energy harvesting for fuel flexibility, (3) thermal science, (4) energy storage and batteries, (5) alternative power, and (6) nuclide power. This research falls within the general S&T areas of energy harvesting, conversion, storage, and delivery. Clear linkages between ARL research programs and Army needs were, in most cases, well presented. Some strong and highly visible programs are internationally recognized and are likely to create opportunities to improve effectiveness of Army personnel in the field. In addition, there are less visible although essential efforts providing incremental advances specific to Army needs.

Accomplishments and Advancements

The team working on aqueous lithium-ion battery (LIB) materials and systems is making exceptional advancements in the S&T of electrical energy storage with lithium-ion batteries. Aqueous electrolytes are nonflammable and thus dramatically safer than conventional electrolytes for military use. This ARL team has advanced the science of ultra-concentrated aqueous electrolytes that has enabled the use of high-voltage electrodes that previously were incompatible with aqueous systems. Work by the ARL team spans a broad range from computational modeling of interfacial chemistry to fabrication of cells of a size (approximately 5 Ah) suitable for field use. This is a wide range of activity for a relatively small group that has deservedly garnered positive international recognition.

Work on wireless energy transmission is also making excellent progress with capabilities, for local wireless energy transmission (centimeters to meters) using electronic and acoustical waves, and is among the best in the world.

Emerging work on chemically powered artificial muscles is at a very early stage but holds potential for improving upon human muscles for applications in legged robot transport (“mule”) and powered exoskeletons.

Steady progress has been made in improving the power of beta-voltaic batteries using conventional nuclear materials (e.g., a 0.8 W/kg battery was achieved using improved collection of beta particles emitted from ^{63}Ni). A potential breakthrough advance was achieved by demonstrating nuclear excitation by electron capture (NEEC) that could enable creation of nuclear isomers having favorable properties for multiyear electrical power generation, without need for recharge.

Advances in electrocatalysis and photoelectrocatalysis will improve capabilities for energy harvesting and conversion in the field, and advances in phase-change materials will improve packaging for high-energy electronics.

Recent reorganizations within the Army, particularly involving the Futures Command and the Concepts & Operations group are positive developments. The “Team Ignite” program, linking ARL researchers with Army future concepts writers, received much praise for opening communications about what is possible, and what is needed to enable the possible to become real.

Chemically Powered Artificial Muscle

This area within the energy science group is derived from ARL director’s initiative that supports projects in the energy science area and in the sensors and vehicle technology areas. The overall goal of the research is to develop materials and technologies to convert chemical energy from fuels directly into mechanical energy with relatively high-energy efficiency, high power, and fast response without a need for intermediate electrical systems—for example, fuel cells and electrical actuators. Army interest in such technologies derives in part from their potential utility in legged robotic transport, powered warfighter exoskeletons, and other areas. Chemically fueled artificial muscles that could improve upon performance of human muscles could offer technological advantages to the Army in many ways. Three posters were presented which described various combinations of fiber materials—for example, carbon and polymer fibers, with electronically conductive or ironically conductive polymers, to make chemically powered actuators.

Army work to date is at a relatively early stage, with strong collaborations with national leaders providing a starting point but with Army researchers mostly in a learning and following role, studying materials that are not greatly different from those being studied by others. The team has demonstrated several fiber- and film-based configurations that exhibit actuation upon chemical stimulation. These include carbon fibers (carbon nanofibers and nanotubes) combined with various ionically and/or electronically conductive polymers, interpenetrating networks (IPNs) of redox polymers (e.g., polyaniline) with ionically conductive polymers (e.g., sulfonated poly-ether-ether-ketone, or SPEEK), and electrospun fibers made from poly-4-vinyl pyridine and from poly-acrylonitrile. In many cases, the composite materials include integrated catalysts—for example, Pt-group-metal particles, which catalyze fuel oxidation or oxidant reduction. Actuation is achieved by treatment with various chemicals including solvents, aqueous solutions of varying pH, and chemical fuels or oxidants. Fuel is in most cases hydrogen gas and oxidant is oxygen gas. Actuation mechanisms likely derive from a combination of solvent swelling/deswelling, ion exchange, and oxidation/reduction of components in the fibers. A 1 kg load was lifted more than 1 cm by a solvent-actuated fiber that was the program target and is more than 10× larger than current state of the art. Reversible redox actuation of a finger-shaped object was demonstrated with approximately 2 Hz frequency, and a light-activated fuel-powered actuator was shown to exhibit a work capacity of 50 J/kg that is approximately 6 times larger than a typical mammalian muscle work capacity.

Energy Harvesting for Fuel Flexibility

The overall goal of this effort is to operationalize foundational research to unburden the soldier/squad with a focus on logistics reduction, mobility, situational awareness, and survivability. Specifically, energy supply in the battlefield is limited by logistics resupply and the amount of fuel and number of batteries carried, thus energy harvesting is an important focus of ARL research in energy sciences. ARL is the leading organization researching needed energy for future Army systems and capabilities.

The seven projects presented in this area were (1) enabling multifunctional materials design and analysis for energy and power; (2) photomechanics of plasmonic photoelectrocatalysts; (3) polarization fields in iii-nitride polarization field enhanced solar water splitting; (4) electro-oxidation of urea for hydrogen generation and cleaner water; (5) efficient hydrogen generation from hydrolysis of nanostructured aluminum alloys; (6) synthesis and investigation of new catalytic materials for the effective in situ hydrodeoxygenation of biomass derived oil; and (7) single-atom catalysis for conversion of methane (natural gas) to liquid fuels.

Overall, the projects are deemed successful and well aligned with the needs of the soldier. Researchers in this area have published 53 peer-reviewed publications and received 7 patents since 2018. A wide range of energy harvesting/conversion technologies were observed with a common theme for most projects being catalysis for energy conversion. The development of a heuristic methodology for the design of multifunctional materials, which is 4 to 6 orders of magnitude less expensive than finite-element analysis, is noteworthy. The technique was verified and validated for mechanics and multiphysics satisfying Onsager reciprocity relations. Progress is reported on some relatively high-risk schemes for coupling solar energy into electrochemical reactions to create and use chemical fuels, with a particular focus on catalysis. The power of harvesting solar energy in this way is impressive. ARL researchers have created molecular beam epitaxy-grown pseudomorphic layers of InGaN whose strain coherency supports polarization fields in the c-plane direction, which is useful for solar energy harvesting. Catalyst materials and reactor designs are demonstrated for value-added chemical and fuel production, particularly involving biomass hydrodeoxygenation and methane conversion to liquid fuels.

Thermal Science

The need for efficient electronic cooling is important as device heat flux continues to increase. To mitigate the heat generation, engineering solutions are put in place for thermal management; however, these solutions are optimized for peak-load conditions and many systems only operate at peak load a very small percentage of the time, and only for a fixed duration. Phase change materials (PCMs) absorb heat in transience. Because the effective heat capacitance increases significantly during phase change, it enables absorbing a large quantity of heat with theoretically no change in temperature difference and hence minimal thermal budget and reduced maximum junction temperature, T_{jmax}, for applications ranging from batteries to electronic/photonic devices. The performance of PCMs is related to its Figure of Merit (FOM), and FOM = *kpL*, where *k, p*, and *L* are the thermal conductivity, density, and heat of fusion. Three posters were presented: (1) 3D fabrication of NiTi PCMs and characterization in partnership with Texas A&M University (TAMU); (2) a novel technique to measure thin-film thermal conductivity, and (3) development of a MATLAB-based ParaPowertool as an open source resource for co-design and exploration of PCMs.

In the first poster, collaborating with TAMU, the team adopted a multitiered approach to fabricate, characterize, and model traditionally manufactured and additively manufactured NiTi alloys. NiTi represents a 3D printable, high-conductivity, form-stable, high-capacity, solid-state PCM; and the parameters can be adjusted and optimized during fabrication. The facilities at both TAMU and ARL are excellent. Excellent progress is being made including publications at conference proceedings and journals. The path forward is to exceed both the literature reported thermal conductivity and latent heat, which is an ambitious but doable goal.

In the second poster, the team addresses the problem of measuring the thermal conductivity of thin films, which is important in evaluating FOM. Using state-of-the-art characterization methodologies at ARL for thermal properties of thin films, the team was first to report the thermal conductivity of 4-element NiTi-based shape memory alloy, and then deduce the effect of parameters such as Cu concentration.

In the third poster, the team developed tools that can survey design space to understand trade-offs inherent in phase-change thermal load leveling. The team released an open source code called ARL ParaPower, where co-design and parametric exploration are accessible to researchers. This is quite significant, as the alternative of multiphysics modeling, using computational techniques, is very CPU (central processing unit) intensive and for all practical purposes cannot be used as a design tool on its own. The hierarchical design approach that has been implemented positions ParaPower as the back-of-the-envelope calculator and then couples it to more detailed computational multiphysics models. ParaPower will be quite handy for teaching, such as in an undergraduate heat transfer or thermodynamics class, as well as being quite useful for research purposes. The work can be showcased at events such as the Semi-Therm Fall Thermal Workshop or present tutorials at ITherm conferences and Electronic Components and Technology Conference (ECTC).

This is a very strong team with potential for important breakthroughs. The results achieved to date are very good. It is worth pointing out that the projects are not stand-alone and that they complement each other and will reduce development lead time. The team is working closely with universities such as TAMU and University of Maryland on material development, and they appreciate the importance of interns as a great way to educate future students in the field. This is also a potential path to recruiting, which ARL seems to have already implemented.

Energy Storage and Batteries

The energy storage and batteries efforts within the energy sciences group seeks to establish the fundamental knowledge base of electrical energy storage technologies. This emphasizes batteries, to enable the development of devices that are, above all, safe, while delivering high energy, high power, fast recharge, and long cycle life. A number of the efforts were well defined and integrated, while others were somewhat less so. The effectiveness of today's warfighter increasingly hinges on the capabilities of multiple devices that depend almost exclusively on portable electric power. Thus, there is a great impetus to develop electrical energy storage technologies that can deliver high energy for length of use, high power for intense use, with fast recharge to minimize "off" time, with long cycle life to minimize replacement, and that are above all, safe. This last point is critical because in numerous cases the battery would be in contact with or very close to the warfighter.

Without a doubt, the most important and impressive accomplishment has been the development of the ultra-concentrated 63 m electrolyte (42 m LiTFSI + 21 m $(Me)_3$Et N·TFSI). This accomplishment has enabled the development of water-based 4.0 V lithium-ion batteries. This paradigm-changing development has enabled the development of nonflammable lithium-ion batteries. In essence, the ultra-concentrated electrolyte expands the voltage stability window by delaying the evolution of hydrogen and oxygen. This body of work was extremely well integrated with theory and modeling going hand-in-hand with experimental developments. The theory component was excellent and set the ground for the technological aspects of the work, including batteries based on halide intercalation and a 4.0 V nonflammable lithium-ion battery.

There was a poster related to the development of zinc metal batteries. While this is an area that has been studied extensively for many years, there is a great deal of divergence in the published literature. The ARL group is developing and establishing a testing protocol intended to "organize" and provide a common footing for those results. While the program is still in early stages, the outlook appears promising.

There were also presentations dealing with more traditional battery materials and technologies, including the use of NMC-811 (NiMnCo) as fast-charging cathodes, the use of nano-scale Si/silicide anodes, as well as the development of a low-temperature protocol for the synthesis of TNO ($TiNb_2O_7$) for fast-charging anodes. These studies were not considered to be at the same level of excellence as the work described above.

The computational and experimental work on the ultra-concentrated electrolyte is excellent, and the group is commended for the very high quality of the work, its excellent integration, and the large number of high-quality publications. This area is uniquely associated with ARL, and is considered to be of the very highest quality in the battery community. The work on Zn metal batteries is getting started and has a good trajectory. The work on more traditional materials was not at the level as that described above.

Alternative Power

The alternative power efforts within the energy science group includes work on wireless power transmission by several means, power conversion by thermal (pyroelectric) methods, energy storage in 3D dielectric capacitors, and energy conversion by electrolysis (focus on electrocatalysis of alkaline oxygen evolution reaction—OER) and by fuel-flexible combustion via an emerging type of combustion flame. A common theme in the work is that all the projects involve some form of energy transmission, reception, or conversion. Each project improves or seeks to improve on the state of the art for energy transmission or conversion efficiency in ways that would be beneficial to the Army, including warfighter power, autonomous vehicle charging, and wearable sensors. Army operations are increasingly energy-intensive, and technologies that provide Army teams in the field with energy via efficient transmission or conversion from battlefield resources are highly valued.

A group of projects focuses on wireless energy transmission via various transmitted and received waves, with each project focusing on a different type of wave and distance for transmission. Electrical-induction-based wireless energy transmission is accomplished using mechanically stretchable inductor coils made from liquid metals entrapped in closed channels within silicone polymer sheets. Wireless energy transmission efficiencies above 90 percent are achieved for stretchable single inductor coils in near contact and near 50 percent for coils at a distance approximately twice the coil diameter. These transmission efficiencies are among the highest reported for stretchable and wearable materials, and the ARL team is among the best in the world in this area. High-frequency acoustical wireless energy transmission is well suited for longer distances—for example, tens of cm—and is accomplished through air and metals and through air-filled metal tubes. Effective strategies for focusing energy at transmission and reception points are developed and provide improved transmission efficiencies. Acoustical energy transmission lacks an electromagnetic signal and is thus well suited for clandestine operations. Piezoelectric resonators are coupled with custom electronic circuitry to create very-high-gain voltage-to-voltage amplifiers for use with low-power wake-up receivers. Voltage gains above 100 are obtained for a single-stage resonator made from quartz, for which a very high Q-factor for the mechanical resonance is found to be the most critical factor for achieving high amplification. These high gains are a significant improvement on prior work and are highly beneficial for low-power wake-up receiver devices—for example, for remote sensing.

Advanced pyroelectric materials are showing potential for heat-to-electrical energy conversion that could be accomplished to utilize waste heat and to transmit energy at a distance via high-power lasers. Three-dimensional dielectric capacitors are created from a 3D-printed carbon mesh onto which is deposited a layer of Al-doped HfO_2—a well-known antiferromagnetic dielectric—followed by back-filling the structure with liquid metal to provide conductors on each side of a thin dielectric. High-energy storage is achieved per unit volume of dielectric with fast response and long cycle life for relatively low applied biases—less than one-quarter of the dielectric breakdown field strength—as is expected for the chosen dielectric material. Approaches to using pyroelectric materials for heat-to-electricity conversion were also presented, in one instance using a laser-irradiated pyroelectric film to charge a battery.

Work on electrocatalyst development for oxygen evolution in aqueous alkaline electrolytes was reported for a combination of a FeNiCo oxide spinel with a MoS_2 support. The combination of the FeNiCo oxide with MoS_2 yields an electrocatalyst with particularly low overpotentials for the OER. Last, ARL has learned important new aspects of the blue whirl, an emerging type of liquid-fuel-fed flame that is particularly flexible with regard to fuel source. Details on flow dynamics within the flame have been elucidated, and devices for containing the flame have been created for coupling with heat-to-electrical or heat-to-mechanical energy conversion devices such as a Stirling engine.

The overall technical work quality is high, with some work being of very high quality. The wireless energy transmission work and the low-power wake-up receiver work is equivalent to or better than that from the best groups in the world. The ARL team has a holistic view on wireless energy transmission that likely gives it a valuable perspective on how best to approach energy transmission for various application details. Pyroelectric energy conversion work is of high quality and is generating significant publications in high-impact journals. The capacitive energy storage and electrochemical conversion work advances the state of the art but is generally similar to other related works.

Nuclide Power

The nuclide power efforts focus on providing power to greatly extend and sustain Army operations at multiple scales by looking beyond fossil fuels and conventional technologies.

The three projects presented in this area were (1) nuclide power to move beyond fossil fuels, (2) first demonstration of nuclear excitation by electron capture for radioisotope energy release, and (3) maximizing beta interactions in textured energy converters. Researchers in this area have published 17 peer-reviewed publications since 2018.

Key objectives of this program include the determination of feasibility of switching radioisotopes from long-lived excited states (isomers) to short-lived ground state using NEEC for novel, disruptive power sources, and maximization of power-source power density for sensors and communications electronics. The latter is aimed to be achieved through use of energy-dense radioisotopes (RIs) and textured wide-bandgap semiconductors for decades of persistent sensing (IoBT) and communications (SatCom) with a goal of 10 mW/cc. The ARL team has for the first time achieved an experimental demonstration of NEEC. This is an important advancement that could enable creation of future portable nuclide-based electrical power sources. Incremental progress is being made using conventional radioisotopes to create beta-batteries. A betavoltaic power source with power density of 0.8 W/kg has been achieved with a goal of 10 W/kg.

This relatively small program has achieved excellent results. The program has significant collaborations with many external organizations that enhance the impact. A small accelerator will be installed at ARL soon that will move this program forward. There is currently only one full-time person dedicated to the betavoltaics program. Additional researchers would be necessary to continue growing this effort.

Challenges and Opportunities

Chemically Powered Artificial Muscle

This early-stage project provides great opportunity and great challenge. The opportunity to create materials that can provide chemically driven actuation better than human muscles is attractive and important. The preliminary results are intriguing, but much progress is needed before field deployment could be considered.

The project would benefit from a clearer definition of property/performance metrics and testing protocols for artificial muscle materials and devices to drive advancement and aid in decision making going forward. Improvements on existing technology are needed in mechanical strength, speed, efficiency, force, energy efficiency, and other areas, but these improvements are for the most part not linked to quantitative metrics. ARL needs to undertake efforts to develop such links to quantitative metrics. New materials and systems need be compared with existing natural and artificial materials and quantitatively evaluated against the needed improvements. Work capacity (i.e., J/kg) is one useful metric that was used by the ARL team to characterize some materials and systems, and it could be used going forward if it was defined more precisely and linked more carefully to potential uses for artificial muscles. Another more important metric is power. Muscle is important in part because it can provide high power when needed, and artificial muscles need to be compared with natural muscles on this basis. The artificial muscle field is at an early stage at which comparisons of materials and systems is difficult because of a lack of common testing protocols and metrics. Army researchers could fill this need by defining the most relevant metrics and tests for those metrics. Thoughtful engagement by ARL researchers regarding metrics could help propel the ARL team to a leadership position.

A clearer focus on mechanisms would be useful. There could be a clear distinction between actuation driven by energy stored in fuels and actuation from processes such as solvent and pH-induced swelling/deswelling, which are not likely to be useful for reversible high-power muscle actuation. The Army work would also benefit from a clearer comparison with prior works and alternative approaches to creating artificial muscles. A 50 J/kg work capacity for Army materials is good, but work capacities 75 times higher than this that are almost 100 times higher than typical mammalian muscle work capacity have been reported using other means—for example, electrochemical—to actuate artificial muscle materials made from carbon nanotube yarns that are not greatly different from the materials used in these projects. Army work needs to be viewed in the context of these related works.

Computational modeling has so far not been applied in this work by the Army or others, but it could provide valuable insight into how systems operate and what might be possible. The team plans a modeling effort soon that could present an opportunity for advancement. The team will at some point need to quantitatively consider transport rates within the muscle materials because those rates ultimately limit power. Systems for delivering fuel or oxidants, and combined propagation rates of redox conversion with solvent and ion motion within materials, will be critical and will need to be clearly defined to enable modeling. The Army team could be positioned to make significant progress in this area, which could lead to a deeper understanding of what level of material and device performance might be possible

The ARL is a relatively new player in the artificial muscle field and the work presented was for the most part closely linked to prior work from other more established groups. The materials presented are sensible but not greatly different from materials being used by others. The team does not yet have a strong publication record, so the technical quality is somewhat difficult to judge at this stage. The team is still building its capabilities and establishing its place in the artificial muscle community. Collaborations with University of Texas, Dallas, Vanderbilt University, and others link the Army team to groups with valuable expertise. The unique feature claimed for Army work is that actuation is achieved from chemical fuels rather than other means—for example, electrical—which is important. This unique position needs to be more strongly emphasized, so it can drive innovation and technical quality.

The Army effort would benefit from greater exposure to and integration with other artificial muscle teams globally, and from a greater focus on quantitative metric and test protocol specifications.

Energy Harvesting for Fuel Flexibility

There is an opportunity for the team to use utilize topology optimization and machine learning for improved materials design. Studies using solar energy harvesting and "hot" electrons to overcome kinetic barriers in electrode reactions are challenging because of the many ways that solar irradiation can affect electrochemical behavior. The team has an opportunity to do definitive work by focusing on reaction rates and product distributions, particularly for fuel production, and not just on changes in cell current.

ARL needs to continue the work using plasmonic photothermal enhancement for reductive chemistry—for example, CO_2 reduction to fuel with plasmonic Cu—but with clearer focus on rate enhancements and product formation. ARL needs to study new materials, structures, and compositions to observe plasmonic heat generation at the ultrafast time scales. In addition to current work in surface plasmon resonances, polarization fields are attractive for research in photocatalysis systems.

ARL could benefit further from looking at producing urea as an energy carrier as an alternative to ammonia itself, which could be generated from air and water in the longer term powered by micronuclear energy sources at the front. Both nitrogen-based energy carriers are far more dense than compressed hydrogen and useful in manpower applications as well as in UAV fueling, operated on fuel cells rather than thermal conversion or combustion approaches. ARL could explore catalytic enhancements to improve production of hydrogen and nitrogen-based energy carriers, and decomposing these carriers back to hydrogen for fuel cell applications.

Thermal Science

This research may have broad applications and with these levels of work could be adopted in multi-chip modules in micropower electronics systems such as 2.5 and 3D packages. ARL needs to work with commercial code companies like ANSYS to integrate ARL ParaPower so that it can be used more broadly. It was pointed out that the team interacts with the Center for Power Optimization for Electro-Thermal Systems (POETS) team at the University of Arkansas, and that is a good gateway to the POETS power electronics National Science Foundation Engineering Research Center.

There is great potential for recognition such as being named a fellow of societies, but this requires senior-level mentorship, so employees know the criteria for such recognition early in their career. It is also very important that the researchers continue to get funding to travel and present their findings, as it is an essential way to both interact and be recognized by peers. It is important to be able to purchase equipment on a timely basis. The peers of ARL can order equipment more easily, and an inability to do this will put the ARL team at a disadvantage.

Energy Storage and Batteries

The development of the ultra-concentrated electrolyte has enabled the development of nonflammable lithium-ion batteries. However, initial results have shown that batteries made using these systems show poor coulombic efficiency, low power, and rapid capacity fade. In order to achieve the full potential of this development, ARL will need to identify the degradation mechanisms and ways to mitigate them. However, if they are able to do so, it will represent a true breakthrough.

The development of the ultra-concentrated electrolyte for LIBs represents the signal accomplishment of ARL in the electrical energy storage area. Understanding and developing solutions to the factors leading to poor coulombic efficiency, low power density, and rapid capacity fade would represent a dramatic advance, and ARL needs to pursue such efforts. Zn metal batteries represent a promising venue for Army applications. The initial efforts for developing and establishing well defined testing protocols will be of great value to the Army and to the community at large. This is an early effort with great potential. Work on fast-charging anode and cathode materials such as NTO and surface-treated NMC811 provides important incremental advances toward the Army goal of 10 C charging. Work on silicon anodes could contribute to the development of a promising anode material.

Alternative Power

Wave-based wireless energy transmission offers excellent opportunities for technology advancement for the Army. The already-high efficiencies for energy transmission could be further increased by improvements in transmitter and receiver design. Some of the technologies in this project group could be developed to the point where integration into a wearable or field-deployable device may be appropriate. This would challenge the team to test its technology in nonoptimal situations—to test performance and develop applications that align with the unique advantages of the various approaches to wireless energy transmission. Experience gained from such testing would inform the work to develop improved materials and devices.

The 3D capacitor work has made significant advancements beyond the usual planar cells used in dielectric material testing. Three-dimensional structures will almost certainly be needed for high-power applications, and this is a good approach. Even so, the devices as configured are likely to have a low mass fraction of dielectric material, and therefore a low system-level energy density. It would be useful to model the expected system-level energy density and compare it with existing state of the art devices. A focus on increasing mass fraction of active material in the devices while retaining high internal surface area and high-applied fields would likely be beneficial. Concerns about liquid metal penetration into small pores could also be met and be resolved using various surface treatments as noted by the ARL team.

The pyroelectric material work appears to be making steady but significant progress toward useful devices for using waste heat for electrical energy generation. Electrocatalyst work for alkaline OER is advancing a field that is also rapidly advancing in the scientific community at large. Field-deployable configurations will almost certainly involve electrocatalyst integration into alkaline exchange membranes, and the ARL team is planning work in this direction. Work on advanced flames is intriguing insofar as it appears to greatly improve fuel flexibility. Efficiency determination relative to conventional fuel-fed generators is desired, as are quantitative statements about what kinds of fuels are acceptable. Performance metric comparison with other fuel-to-electrical energy conversion devices such as solid-oxide fuel cells, which can also have high fuel flexibility, would be prudent.

An emphasis on the ways in which ARL work is best-in-the-world would be beneficial. Work on blue whirl flames is at a relatively early stage and has made progress, but it is still difficult to tell how transformational the work would be. A more specific focus comparing that work with work on other combustion technologies, and other fuel-to-electricity technologies, would be beneficial.

OVERALL QUALITY OF THE WORK

The overall quality of the management is of high caliber. Researchers are well qualified for their work. ARL's work in preparing for the review was superb, particularly given the uncertainties surrounding this first virtual review.

Most of the projects presented are excellent and, in some cases, world class and may have a pervasive impact on the Army. The scientific soundness and the use of fundamental sciences are outstanding. The project portfolio fits well with both global thrusts and the national agenda.

Collaborations throughout the optical sciences and photonics program were diverse and strong, to the extent that the research advances emanating from these partnerships demonstrates that "the whole is greater than the sum of the parts." That is, the time and effort invested by ARL researchers in developing these collaborations have resulted in a substantial return to the ARL research effort. The fundamental research conducted in the quantum information sciences group is especially impressive and the demonstration of the first communications receiver based on Rydberg atoms is a major milestone of which all of ARL can be proud. The successful effort to store information in spin waves is also promising and a credit to this research team. The advanced solid-state lasers group continues to be one of the "crown jewels" for ARL by driving infrared laser technology with the recent achievement of lasing at 3 microns in new, low phonon energy hosts such as barium fluoride and yttrium lithium fluoride. The sensor protection scientific team is commended for the clever iridium chemistry that is being pursued to develop broadband reverse saturable absorption materials and the GMR filters. Among the impressive accomplishments of the integrated photonics research team is the dramatic improvement in the performance of optical frequency combs and the successful demonstration of electrically steerable phased arrays.

Overall, the research projects in the electronics and optoelectronics area were of high quality and comparable to other first-class research organizations. The projects evaluated were well thought out and motivated by Army needs—two examples are emerging materials being explored as a means to increase information and data assessment in the field, and materials-driven antenna design that will address the Army's expanding communications and SWaP-C needs. There was a good mix of exciting high-risk projects and those that support Army near-term applications.

In energy science, clear linkages between ARL research programs and Army needs were, in most cases, well presented. Some strong and highly visible programs are internationally recognized and are likely to create opportunities to improve effectiveness of Army personnel in the field. In addition, there are less visible although essential efforts providing incremental advances specific to Army needs. The team working on aqueous lithium-ion battery materials and systems is making exceptional advancements in the S&T of electrical energy storage with lithium-ion batteries. Aqueous electrolytes are nonflammable and thus dramatically safer than conventional electrolytes for military use. This ARL team has advanced the science of ultra-concentrated aqueous electrolytes that has enabled the use of high-voltage electrodes that previously were incompatible with aqueous systems. Work by the ARL team spans a broad range from computational modeling of interfacial chemistry to fabrication of cells of a size (approximately 5 Ah) suitable for field use. This is a wide range of activity for a relatively small group that has deservedly garnered positive international recognition. Work on wireless energy transmission is also making excellent progress with capabilities, for local wireless energy transmission (centimeters to meters) using electronic and acoustical waves, and is among the best in the world.

RECOMMENDATIONS

The setup for measuring the thermal conductivity of various laser advanced solid-state laser materials as a function of temperature is clearly a workhorse characterization setup with extensive and useful data presented. The group could explore expanding this experiment to include other measurements critical to evaluating laser operation. For thermal lensing, the variation in the index of refraction with temperature dn/dT and the coefficient of thermal expansion a(T) both also contribute to modeling of thermal lensing in laser materials. For some applications, the nonlinear index n_2 is also important. Furthermore, characterization of temperature-dependent excited-state lifetimes yields important insight into relaxation pathways. Not everything can be done in one setup, and some measurements are easier than others are. However, the ARL group is in an excellent position to raise its visibility as the "go to" group for materials developers seeking a laser materials characterization capability in the United States, which would prove to be of considerable benefit to both the ARL and U.S. laser efforts.

Recommendation: The Army Research Laboratory (ARL) should raise its visibility toward being the "go to" group for materials developers seeking a laser materials characterization capability in the United States, which would prove to be of considerable benefit to both ARL and U.S. laser efforts.

In the area of RF and digital electronics, there are many opportunities to validate the approaches proposed prior to significant investment of time, energy, and money, and further to determine who would provide such validation. As presented, the performance metrics expected and needed for further investment have not been defined, with an opportunity to establish go/no-go points. A challenge is also presented in the relatively limited approaches to address each project; this introduces the concern that industry and commercial vendors could meet or surpass any successes within the same time frame. In development of hardware for neural network and protection of integrated circuits, niche applications have been identified, and would benefit from being put into the context of current state-of-the-art and competitor approaches for validation and development of go/no-go gates. As presented, these works are relatively narrow, and no contingency plans or varied approaches were presented.

Recommendation: The Army Research Laboratory (ARL) should qualify its work as soon as possible, as well as articulate performance metrics that must be satisfied to justify work continuation. Industry should be substantively involved in performance metric development as a means of developing realistic go/no-go metrics for commercial investment and success. Following that, ARL should expand the scope of the work in line with the stated metrics in order to increase options for success.

Chemically powered artificial muscle is an early-stage project that provides great opportunity and great challenge. The opportunity to create materials that can provide chemically driven actuation better than human muscles is attractive and important. The preliminary results are intriguing, but much progress is needed before field deployment could be considered. The project would benefit from a clearer definition of property/performance metrics and testing protocols for artificial muscle materials and devices to drive advancement and aid in decision making going forward. Improvements to existing technology are needed in mechanical strength, speed, efficiency, force, energy efficiency, and other areas, but these improvements are for the most part not linked to quantitative metrics. ARL needs to undertake efforts to develop such links to quantitative metrics. New materials and systems need be compared with existing natural and artificial materials and quantitatively evaluated against the needed improvements. Work capacity (i.e., J/kg) is one useful metric that was used by the Army team to characterize some materials and systems, and it could be used going forward if it was defined more precisely and linked more carefully to potential uses for artificial muscles. Another more important metric is power. Muscle is important in part because it can provide high power when needed, and artificial muscles need to be compared with natural muscles on this basis. The artificial muscle field is at an early stage at which comparisons of materials and systems is difficult because of a lack of common testing protocols and metrics. Thoughtful engagement by Army researchers regarding metrics could help propel the ARL team to a leadership position.

Recommendation: The Army Research Laboratory (ARL) should define the most relevant property/performance metrics for chemically powered artificial muscle and tests for those metrics.

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Propulsion Sciences

The Panel on Propulsion Sciences at the Army Research Laboratory (ARL) conducted its review of selected research and development (R&D) projects of the ARL propulsion sciences research core competency during a virtual meeting on June 8-11, 2020. The research areas reviewed were platform power, platform design and control, and intelligent maneuver.

As described by ARL, the Combat Capabilities Development Command (CCDC) ARL's research investments in the propulsion sciences core competency are focused on gaining a greater fundamental understanding of advanced propulsion and platform technologies to inform and enable enduring cross-domain maneuver of air and ground (manned and autonomous) operations in multi-domain operations (MDO).[1] This serves as a key enabler of innovative vehicle configurations and subsystem architectures that are critical to the future Army's movement and maneuver. Knowledge gained through fundamental and early applied research efforts will lead to technologies that overcome the constraints on design, fabrication, integration, control, propulsion, and vehicle intelligence to support reliable mobility and ensure power projection superiority for the future Army. The propulsion sciences core competency builds on fundamental pillars of science and technology (S&T) to conduct research in manned and unmanned Army air and ground platforms that are critical to the future Army's movement, sustainment, and maneuverability to "operationalize science for transformational overmatch."

The goals of the propulsion science core competency area are to discover, innovate, inform, and transition S&T-enabled capabilities that significantly increase the force effectiveness of the Army's air and ground manned and unmanned systems in future MDO and cross-domain maneuvers.

The vision of the propulsion science core competency area is to create disruptive and game-changing vehicle-centric technologies for the Army through utilization of ARL and partner expertise and facilities in combustion physics, propulsion sciences, aeromechanics, intelligent mechanics, vertical take-off and landing (VTOL) design and analysis, aviation component and structural materials, autonomous systems, robotic mobility and manipulation, and state-of-the-art modeling and experimental facilities.

To realize this vision, the propulsion sciences core competency is organized by ARL around three primary research areas in platform power, platform design and control, and intelligent maneuver. Multidisciplinary approaches explore the intersections and span all three research areas in order to create disruptive and game-changing vehicle-centric technologies to inform the Army's future vertical lift platforms, next-generation combat vehicles, and robotics and autonomous systems.

PLATFORM POWER

The platform power research area focuses on understanding and exploiting innovations in energy sources, storage, generation, conversion, transmission, distribution, and management. The goal of this

[1] See https://www.arl.army.mil/what-we-do/foundational-research-competencies/, accessed August 25, 2020.

research is to provide power and propulsion technologies and configurations to enhance the Army operational effectiveness of both manned and unmanned air and ground systems through improved reliability and efficiency, increased power densities, expanded range of fuel sources, and reduced power source acoustic signatures, all of which are critical in ensuring Army power projection superiority.

Accomplishments and Advancements

Overall, the quality of the briefings and posters in the platform power group was very good. The overall research program is commendable, with high scientific quality. ARL has made remarkable progress in implementing the Army Research Laboratory Technical Assistance Board (ARLTAB) recommendations from the 2018 assessment in certain areas, such as establishing collaborative relations with universities and national laboratories in the study of ignition and combustion characteristics at altitude conditions for various fuels and fuel blends of interest. Collaborative efforts have helped to improve the technical quality of the program and made use of state-of-the-art experimental facilities and models to achieve the objectives. The program now reflects a better balance between experimental and theoretical approaches, the latter including computational efforts. ARL would now benefit from seeking to improve the in-house capabilities in these areas via interactions between ARL researchers and their collaborators.

The program on tribology and lubrication science is well formulated and aimed at understanding fundamental physics. This program has demonstrated commendable use of experimental facilities in fundamental research. Application of this capability to study the failure mechanisms for fuel pumps is an excellent application of fundamental capability in resolution of relevant problems—for example, operation using different fuels and under different atmospheric conditions.

The research program on development of coatings for austere environments addresses a very relevant problem; however, its objectives are overstated.

There were several excellent presentations by tenured and early-career researchers; this indicates a positive, material response to the ARLTAB 2018 recommendation to pursue developing a robust workforce pipeline.

Effects of Fuel Blending on Ignition and the Impact for Simplified Ignition Models

ARL has made very good progress in implementing the recommendations provide by the ARLTAB in 2018. In particular, the research program in ignition behavior of blended and alternative fuels has made remarkable progress in establishing collaborations with Sandia National Laboratory (SNL) in experimental as well as computational efforts. The group has collaborations with Argonne National Laboratory (ANL) and university partners as well. Collaborative efforts have helped improve the technical quality of the program and made available state-of-the-art experimental facilities and models to achieve the objectives. The program now reflects a better balance between experimental and theoretical approaches, the latter including computational efforts. The research team is improving in its experience level and is making good use of the complementary capabilities available from SNL. There is room for improvement in the technical quality of the work via a clearer articulation of the motivation and challenges. Collaborations with universities have helped to cover overlapping pressure-temperature phase space. There needs to be a demonstrated effort to co-publish with collaborators in first-level journals as a matter of raising the technological image and impact of ARL research.

Spray Breakup and Atomization in a Combusting Environment

Applying X-ray imaging to study spray breakup at the nozzle exit under realistic combustion conditions is an exciting new area of research for ARL. The presentation clearly laid out the inadequacies of current laser and other optical diagnostic techniques. The ability to visualize how spray evolves after leaving the nozzle is exciting. This experiment generated a tremendous amount of data owing to high speed and spatial resolution. The present data analysis methods need to be improved to integrate the various data acquired into a dynamic and multidimensional description of reaction inception, and rate of heat evolution in multiphase combustion conditions.

Understanding Energy-Assisted Ignition and Its Sensing and Control Methods

This work represents a part of a larger set of projects arrayed around diversifying the fuel supply to have the ability to use a wide array of fuels that might be available in different places or from different sources. This particular project is based on the fact that some fuels have lower ignitability, and some method of coercing those fuels to burn is necessary in compression ignition (e.g., diesel) engines. The method used is a hot surface, which can reduce the time for a fuel charge to ignite and generate heat. The hot surface ignition principles could align the heat release profile appropriately with crank angle to generate optimal power conditions for diesel combustion conditions. This work is part of a set of projects dealing with fuel for compression ignition engines. The objective of this project is to sense whether the engine or even a specific cylinder is igniting properly and to light up the ignition assistant if it is not.

The ARL group is collaborating with an appropriate selection of university investigators. It is a broadly based investigation by ARL into the use of fuels that is easy to employ and would be necessary for military engines in the future.

Nonintrusive Ignition and Combustion Sensing for Engine Feedback Control of Variable Energy Assisted Compression Ignition Engines

This work focused on unmanned aerial systems (UASs) and their respective fuels. The challenge is the wide range of combustion characteristics for multifuel-capable engines. To address this challenge, new sensor technology is being developed to capture combustion properties of reacting systems in nonintrusive ways such that the harsh environment of the combustor does not influence or destroy the sensor and measurements. The work scope replaces an in-cylinder pressure sensor with an outside situated vibration sensor. The advancement here is in making measurements that correlate pressure readings to vibration readings. The outcome is very promising in that some fuels depending on cetane number and enthalpy release behavior correlate very well with the pressure sensor measurements—that is, start of combustion based on pressure aligns with vibration. This is innovative work. Much data still need to be collected and analyzed and applied to real-time engines. This work could benefit from a more rigorous data analysis.

Multi-Injection Mixture Preparation and Ignition in Unmanned Aerial Vehicle Intermittent Combustion Engine Conditions

This poster presentation complements the technical briefing discussed above. The two presentations together do a good job of providing a more complete picture. The comments above encompass both presentations.

Development of a Hybrid-Electric Propulsion Optimization Tool

This work focused on developing an optimization tool for the propulsion system of hybrid-electric vehicles. The approach was to develop optimization algorithms that consider empirical and theoretical models of components within the engine system—engine, motor, energy storage, and thermal management. Preliminary results suggest great sensitivity to the thermal management system. The presentation shows only simulation results. Some simulations were validated by experimental engine results at altitude. Future work needs to develop more experimental observations on which to test simulation predictions.

Design and Analysis of Non-Contact Magnetic Gears

This work is done in collaboration with Texas A&M, a well-known expert in magnetic gears. The topic is not, in itself, novel, as magnetic gears have been a topic of interest for some years. However, the objective of the ARL project is to improve the power-to-weight ratio. The team has chosen to use Halbach array magnets to eliminate the need for back iron.

The choice of Texas A&M as a partner is good. The investigator is well qualified to do this work, and the collaborators in academia are among the most well known in the field of magnetic gears. This background and the ARL uniqueness were adequately articulated.

Numerical and Experimental Investigation of Vibrations in Compact Aviation Turbomachinery

This work is about a failure that occurred in a turbo compressor operating at altitude—it appeared to be a high-cycle failure of compressor blade tips, likely because of vibration. The vibrations of the blades were sensed by one of the three accelerometers, and a separate sensor determined rotor position so that individual blades could be identified.

This experimental work is of high quality, comparable with other leading laboratories, and the investigator is very well qualified. The equipment used in the experimentation is of high sophistication. This work is integrated with other investigations at ARL.

Aluminum Superalloy Structures and Processing Science for Propulsion

This is a metallurgy-based study of materials for use in low production volumes for unmanned systems. The materials were subjected to higher combustion pressure and duty cycles that increase stresses. Commercial alloys based on Al lose strength under these thermal conditions. New ternary mixtures are being considered and produced based on Al, Ce, Zr, Mg, Cu, Mn, and others. Results suggest that Al-Ce-Mg properties have good potential. Results reveal mechanisms for strengthening that have implications beyond this application. The approach has been successful based on the multiscale attention and investigation of the microstructure. Two specialty techniques bring new insights into this work: in situ X-ray measurements of crystallization during laser fusing of metal powder beds—that is, metal 3D printing—and atomic probe microscopy that adds nanometer-scale information.

This work was very well formulated, and results show great potential for this application and the science of materials in general.

Surface Characterization and Modeling of the Interfaces Within High-Pressure Fuel Pumps

High-pressure fuel pumps have many sliding interfaces, which are susceptible to wear damages, and the only lubricant is the fuel. Thus, as fuels are varied toward lower viscosity with inferior lubricity, the wear can be more severe. This work performed modeling combined with component-level experiments. One of the unique capabilities of ARL is an in-house experimental fuel stand that can test commercial high-pressure (2000 bar) fuel pumps, which is a big asset for this work.

Determination of Method for Tribological Experiment on Ultra-Hard Coatings in Low-Viscosity Fuels

This work is related to other investigations into the use of alternative fuels in reciprocating engines. This investigation is of hard surface coatings to reduce wear in the parts of high-pressure fuel pumps. At this stage, standard tribological methods were employed, and certain coatings were investigated with a few fuel surrogates.

The investigator was a rising graduate student. The objective of the project was limited to developing an understanding of how hard materials wear under conditions of different fuels and atmospheres. The presentation was clear and has yielded useful results. One interesting aspect was that the tribological experiment was in a glove box so that oxygen content of the surrounding atmosphere could be controlled.

No collaborators outside ARL were identified. However, this work is just getting started. The work appears to be of high standard, comparable to what would happen in top universities, and the equipment employed was good and of current state of the art.

Challenges and Opportunities

The state-of-the-art experimental facilities and innovative approaches have generated a large amount of data. A valuable investment would be to build up in-house data analytics capabilities to better harness new knowledge from these results.

Before delving into the technical details, the researchers need to have a good understanding of current traditional competing technologies. Such knowledge will lead to clearer articulation of the proposed approach.

Hybrid-electric drive encompasses power electronics and electromechanics, and is an important component of propulsion science. This area needs to be integrated in the program portfolio.

Dimensionless quantities Re, We, and Oh were used in several presentations, which is an improvement over previous ARLTAB reviews. ARL could use dimensionless numbers more broadly, beyond fluid dynamics and across other propulsion science programs.

All the programs have followed the ARLTAB recommendations from the 2018 assessment to augment modeling components to complement experimental investigation. A caution on numerical simulations is that they can be forced to agree with experimental data and lose grounding to the physical world. ARL also needs to maintain and develop core competency capabilities in house in addition to collaborations with external organizations.

Spray Breakup and Atomization in a Combusting Environment

The team needs to apply data analysis tools to analyze the large amount of data and describe heat release physics using a dimensionless number. This will permit generalization of the results.

Development of a Hybrid-Electric Propulsion Optimization Tool

The optimization algorithm was not discussed, so a technical assessment of the approach cannot be made. While empirical assessments of performance and optimization of a multicomponent complex system has merit; this research needs to be compared to experimental findings to assess the validity of the approach.

Design and Analysis of Non-Contact Magnetic Gears

The group needs to further examine its assumptions because it is known that Halbach arrays produce useful flux densities somewhat below those of radially magnetized magnets with back iron, and that Halbach arrays take up the whole periphery of their region and so are a bit heavier. That said, Halbach arrays do not require back iron. On the other hand, the required back iron may not be very thick for a radially magnetized multipole array, and the stronger flux density from a radial magnet will have an impact on developed force density.

Combustion-Based Solid-State Portable Power

This research is on system-level modeling to understand energy flow in a proposed device to burn liquid fuel to generate electricity. The rationale behind this proposed device is for quiet power generation to charge batteries, for example, in unmanned vehicles. The proposed device relies on two steps of energy transformation—burning fuels to heat an emitter (chemical to thermal energy) followed by conversion to electricity of the thermal emission with a thermal photovoltaic (TPV) cell (thermal energy to electricity). There is also a filter between the photoemitter and the photoreceptor, but it was not clear what that filter is. Owing to the inefficiency of these transformations, the combined system efficiency is about 5 percent. The maximum combined system efficiency reported in the literature is 5 percent. Most devices are around 1 to 2 percent. ARL's target system efficiency, which is conservative and based on what has been demonstrated for the individual components that would compose a TPV system, is 10 percent.

Comparison with traditional generators (chemical to mechanical to electrical energy), for example, using a Stirling engine, needs to be made to articulate the proposed approach. While the focus was at the system level, explanations on the selected materials and components would have been helpful for the panel to understand and evaluate the project.

Developing Methods for Understanding Material Behavior in Fuel-Lubricated Interfaces to Match Fuel Pump Observations

This is a new ARL effort to understand how different fuels affect the wear properties of an engine. There is a clear difference between testing done in air versus in nitrogen, as well as among different fuels. In addition, many electron microscopy images were shown, but acquiring 3D analysis such as the depth and roughness of the scars (for example, profilometry or optical interferometry) would add value to the research.

Numerical and Experimental Investigation of Vibrations in Compact Aviation Turbomachinery

While the overall program related to turbochargers involves collaborators at highly ranked universities and industrial firms, it was not apparent that this experiment had any collaborators outside

ARL. The researchers need to review the comments provided later under the turbocharger aeroelasticity at altitudes program, as many of those comments are applicable here.

Durable, Stable Ceramic Materials for Propulsion Systems in Austere Environments

This work is to develop sand-phobic ceramic thermal and environmental coatings for turbines. The material proposed is yttrium stabilized zirconia (YSZ) infused with Gd_2O_3 particles, leveraging YSZ's mechanical properties and rare earth oxide's resistance to sand. The preliminary results are not solid enough to draw any conclusions about the promises of these materials—reaction products were not observed, which might be owing to inadequate reaction conditions, and accumulation results do not appear to correlate with GdO concentration. Hence, the project is far from the stated objectives of 25 percent improvement in efficiency and 40 percent in durability. ARL has engaged key stakeholders in this project—the Department of Energy (DOE), Pratt & Whitney, Rolls Royce, Naval Air Systems Command, and the Environmental Protection Agency (EPA). The recent strategic environmental research and development (R&D) program will help advance the project. Two suggestions for improvement are (1) surface chemical properties such as composition (e.g., using depth-dependent X-ray photoelectron spectroscopy or secondary-ion mass spectrometry) and surface energy (e.g., using high-temperature contact angle measurements) need to be better characterized; and (2) testing needs to be conducted with different kinds of sand.

Diagnostic Signal Features from Aircraft Propulsion Bearings in Accelerated Aging Experiments

This project developed a large volume of data indicating features of aging that affect the performance of bearing materials. The cited work in this area did not appear to have any domestic collaborators. ARL needs to recruit and develop U.S. expertise in the area of crack detection in bearings.

Turbocharger Aeroelasticity at Altitudes

This program aims to develop computational models of unmanned aerial vehicle (UAV) turbochargers to predict and remove the onset of fluid-structure interactions causing turbocharger failure. The problem is very relevant, as the turbocharger failures have resulted in UAV crashes. The approach adopted in this program includes a high-fidelity simulation tool encompassing the entire turbocharger—that is, compressor, turbine, rotor shaft, and housing. This model uses computational fluid dynamics and finite element analysis (FEA) methods. The presentation also points to a reduced order aeroelastic lumped parameter (ALP) model. No details of this ALP were provided. The presentation provides three references that form the basis for this model. However, the cited literature is focused on stall and surge in compressors, and it is not clear how that would relate to aeroelastic behavior of turbine blades in the turbocharger. This program needs a focused review of the approach. The two publications listed within this presentation are titles for two conference presentations that are scheduled to occur at some time in the future. The two titles are also almost identical. The researchers need to strive for publications in high-quality journals.

Numerical Methods for Modeling Complex Composite Architectures in Representative Volume Element Development

This work focused on developing a model to accurately predict material responses based on complex architecture. The goal is to move toward greater weight reduction in future vertical lift applications. The study was numerical in nature to down-select experimental approaches that would otherwise be expensive and time consuming. The challenge is that complex loading conditions in a gear or transmission require quasi-isotropic triaxial braided matrix—but geometric modeling of braids without penetrations is difficult. The approach is to use microscopic images to represent architectural defects that lead to non-quasi-isotropic behavior and use novel thermal expansion and compression challenges of high-volume fraction triaxial braids with a linear elastic material model. Results are preliminary and show some promise in comparison to experimental measurements of moduli for isolated directions. Continued development of this model needs to take place with attention to the mesocopic scale that may reduce simulation errors.

PLATFORM DESIGN AND CONTROL

The platform design and control research area focuses on fundamental research that enables the development of the highly maneuverable and tactically adaptive platforms. The research is expected to impact a wide array of vehicle technologies, cutting across the ground, air, and maritime domains, as well as vehicle classes from large- to micro-scale device technologies.

The platform design and control program had nine technical briefings and eight posters presented during the panel meeting. The research topics reviewed included conceptual design and sizing tools for next-generation unmanned rotorcraft configurations and propellers, rotor control methods, trajectory guidance and control, fluid and structural dynamics and fluid-structure interaction, and reconfigurable and tailorable structures.

Accomplishments and Advancements

Overall, the platform design and control research program adds considerable value to the body of R&D knowledge. The laboratory leadership is very connected to projects, objectives, and deliverables. ARL has acted effectively to address the comments and recommendations made by ARLTAB in its 2018 assessment. ARL's focus on modeling small-scale unmanned systems is necessary to develop and employ these emerging machines, and to identify, assess, and pursue relevant breakthrough technologies.

The materials and structures research, with an emphasis on incorporating artificial intelligence (AI), machine learning (ML), and deep learning (DL), represents pioneering of complex, high-risk areas of basic research. This demonstrates that discovery can be disruptive and can have wide-ranging implications for science and innovation in synthesis, and this research needs to continue. Several topics presented represent ARL's extended strategy to explore disruptive topics outside the current core competencies and to identify promising future directions for the laboratory.

While some work is not balancing theory with experiments and simulations, a particular exemplar is the microstructure deep learning that is developing AI/ML approaches by fusing simulation and experimental data. The molecular dynamics modeling in both the computational design of shape memory polymer actuation and the tailorable and multifunctional dynamic polymer networks can provide data to implement AI methods. Dynamic polymer networks research is a unique combination of morphing, self-healing, and shape memory. The non-equilibrium molecular motor research is on the leading edge of bio-hybrid basic research and will help inform ARL in shaping its future portfolio.

The emerging R2C2 facility is a highlight for unmanned aerial system (UAS) experimentation, capitalizing on the opportunity to offer local capability to develop autonomy for the extreme UAS vision. The nascent intelligent mechanics initiative can be disruptive, exploring the historical distinctions between proaction and reaction, such as adaptation, reconfiguration, and control versus deformation and failure.

There are a number of talented early-career researchers who are capable in their disciplines, and they will benefit from mentoring and experience to engender a greater system-level perspective. For example, cross-discipline rotations can be implemented and the technical breadth needs to be expanded.

Tilt Rotor Aeroelasticity Analysis

This is the analysis portion of a combined computational and experimental program to assess the capability for predicting the dynamic instability boundaries for tilt rotor aircraft. The experimental portion of the program has been delayed owing to the COVID-19 pandemic. Dynamic instabilities can lead to catastrophic failure of wind tunnel models, as has happened for prototype rotorcraft in the past. This combined computational and experimental program addresses these critical issues.

Predictions of the dynamic instability boundaries have been made using potential flow aerodynamic models with various representations of the rotor inflow. In addition, several methods have been assessed for extracting frequency and damping of critical system modes from the computational data.

Stacked Rotor Aeromechanics and Acoustics

This is a good exploratory study with improvements observed for metrics including increased efficiency, a thrust change that could be used for control, and reduced acoustics emissions.

Hybrid Design and Analysis of Rotorcraft (HYDRA)

This research constitutes an excellent shift of applicable systems analysis from what was largely empiricism to a far more physics-based approach. Such a shift was necessary for comparative studies of new design precepts and has already proven useful in that regard.

Conceptual Design of UAS with Dissimilar-Size Rotors

HYDRA improves upon the National Aeronautics and Space Administration (NASA) Design and Analysis of Rotorcraft conceptual design tool for Group 1-3 UAS by adding physics-based rotor blade and airframe weight models, support for airfoil tables, increased fidelity rotor power modeling, and rotor/wing/airframe interactional aerodynamics. It combines FEA, blade element momentum theory, a powerful vehicle trim function, and semi-empirical power plant models. This effort opens the aperture on design of distributed propulsion rotorcraft by modifying the HYDRA tool to assess performance of a broad design space of rotor geometry and operating conditions.

The modeling predicted performance improvements available with dissimilar rotors and provided guidance on how the rotor dissimilarity decisions differ with scenarios description (e.g., extent of hovering), but awaits validation through correlation with experimental data.

Common Research Configuration

The common research configuration (CRC) initiative seeks to create a reference vehicle concept for scalability studies across disciplines such as design, aeromechanics, acoustics, and flight control. An additional goal of the initiative is to facilitate collaborations with research partners.

The team has performed a UAS design space exploration to select the quad bi-plane tail sitter configuration for maximum value and as best suited for a research environment. The conceptual design analysis has been performed for a notional scenario at different scales. Additionally, 3 lb and 20 lb configurations have been fabricated and flight-tested to acquire performance data to support analytical efforts.

The use of CRC both for in-house research projects and by multiple research partners has shown that CRC is proving to be invaluable to create a community of interest to advance collaboratively the state of the art in Group 2-3 UAS platform and component technologies. It is excellent that the reference models for Group 1-3 UAS have been utilized by universities investing their research funds, and these relationships need to be continued and enhanced with national laboratories, commercial industry, and other governmental agencies.

Sizing and Performance Tool

This study focuses on physics specific to air launched effect (ALE) class propellers and development of a computational tool for rotor sizing, performance, and optimization analysis to support the ALE concepts, trades, and analyses (CTA) study.

Performance for the two rotors, the ALTIUS UAS propeller and the TRV-150 UAS rotor, were measured to provide data for analysis tool validation. The ALTIUS UAS propeller data were test data from CCDC Aviation and Missile Center and ARL provided computational data. For TRV-150, the data were test data and computational data. Wind tunnel tests of this rotor with various tunnel speeds, rotor speeds, and rotor pitch settings have been completed. A hover test stand has been set up at the University of Maryland, and testing of a matrix of rotor speeds and pitch angles was in progress.

Performance of both rotors was computed using both FUN3D and Helios computational fluid dynamics (CFD) analyses. The CFD analyses provide data for validation of the rotor sizing, performance, and optimization analysis tools for the cases where test data are not available and where flow details are difficult to measure. A rotor performance analysis tool, JBLADE, is evaluated using the test data and CFD analysis results. Based on the discrepancies identified in the evaluation, the JBLADE code will be enhanced to allow a high-accuracy rotor performance analysis over a broad range of operating conditions. The ALE CTA will be performed using the improved tool. This is a good example of using both experiment and simulation and leveraging the strengths of each.

Automated CFD Process for Airfoil Aerodynamics Characterizations

This research produced a method that provides a fast, robust grid for any CFD code and is therefore very valuable. The work was an initial step on the path to incorporating and improving the requisite physics. The meshing achieves structured mesh efficiencies with unstructured mesh robustness.

Turbulence Effects on Airfoil Performance at Low Reynolds Number

UAVs operate at lower altitudes, at low Reynolds number, and at low speeds, which induces separated flow. This work studies the impacts of free stream turbulence of a scale similar to the boundary layer thickness on separation control. The work makes good progress and finds that these effects are analogous to boundary layer transition—that is, imposed turbulence has similar effects to body-generated turbulence in delaying separation.

Tailorable and Multifunctional Dynamic Polymer Networks for Adaptive Structures

This effort explores the viability of engineering materials at the molecular level to make mechanically relevant structures. Employing highly adaptive multifunctional systems with tailorable response and structural elements that are configured based on environment, the research investigates whether a stimuli-responsive dynamic molecule can leverage the intrinsic flexibility of the polymer backbone to achieve on-demand reconfigurability.

This promising research on modeling molecular dynamics is very impressive and a highlight of the laboratory, exploring the unique combination of morphing, self-healing, and shape memory. The early experimental results show promise and could be a game changer. The team could further use the molecular dynamics simulations to provide additional data to implement AI methods.

Non-Equilibrium Molecular Motor-Based Mechanical Actuators: Modeling the Attraction Between Two Charges in an Ionic Solution

This directed biology research is leveraging new techniques in microscopy to inform improved modeling of contractile mammal muscle tissue. The modeling of protein-protein attraction is being used to determine what forces are responsible for guiding molecular motors to their binding sites. This modeling is intended to enable the move from empiricism to first principles, to set the conditions for disruptive design for innovation in robotics.

The researcher brings a strong background in modeling nonlinear dynamical systems, and has developed a substantial understanding of the literature on molecular motors. This good, basic research seeks to establish a path to bio-hybrid robotics, bio-functionalism, and living devices. This research is informing ARL whether to include this in its future research portfolio. Success is not ensured, but this high-risk/high-reward research is worthwhile.

Microstructure Deep Learning

It is well known that material microstructure directly influences the physical properties of a material system; however, the specifics of these interactions can be difficult to quantify because they can be nonlinear and difficult to predict. This research focuses on applying modern deep learning (DL) techniques on scanning electron microscopy material microstructure images in an attempt to quantify relationships between material processing parameters, corresponding microstructure, and subsequent material properties. DL-based approaches applied to material systems are validated on simulated microstructure images of TiAlZrN ultra-hard nanostructured coatings and subsequent processing parameters. This effort is a good example of fusing the simulation data together with the experimental data to develop an AI/ML-based approach. The researchers need to add some theoretical results into the learning for a better understanding of the mechanisms involved.

Parallelized Fluid Structure Interaction for Optimized Aero-Structural Design

By prescribing a small family of structural deformation shapes, the pressure distribution can be computed from a CFD code. Also, by prescribing a small family of aerodynamic pressure distributions, the structural deformation can be computed from a finite element (FE) code. Using these separate fluid and structural data sets to create reduced order models (ROMs) for the flow and structure, these fluid and structure ROMs may then be combined to compute very efficiently the fluid structure interaction of the fluid structural system. This is particularly efficient and straightforward for static, linear analysis. Only static cases have been treated to date, and for the range of parameters investigated, the system response is in the linear range. This work is making good progress.

Deep Learning of Nonlinear Dynamics from Pixel Measurements

Deep learning attempts to extract patterns and models from large data sets. Even when the uncertainties in the data are not well understood, certain general principles, which the data ought to satisfy, are known. For example, conservation of energy might be required, or the system must obey Hamilton's principle, or certain symmetries need to hold. In this work, these general principles are imposed as constraints on the data and on any models that are inferred from the data.

To date, simple examples have shown promise, and a structural beam experiment is planned to provide the next step in this research.

Computational Design and Shape Memory Polymer Actuation for Reconfigurable Aero-Structural Design

A coarse-grained molecular dynamics (MD) computation has been used to identify promising polymer material mixes that can be used as actuators. The materials have been used in experiments performed by university partners to measure desired macroscopic properties—for example, modulus of elasticity. While the MD simulations do not provide quantitative agreement with the experimental measurements, there is qualitative agreement and thus the MD simulations provide a useful guide to selecting promising material combinations.

Modeling and Control Methods for Future Vertical Lift Rotorcraft Fatigue Reduction

Rotorcraft undergo constant vibratory excitation owing to unsteady air loads. Controlling the vibratory loads is essential for improved performance and safety. This research seeks to develop rotorcraft loads analysis methods with fatigue damage estimation and fatigue reduction controllers for future rotorcraft. The research emphasizes the development of a simulation-based predictive capability by coupling a state-of-the-art rotorcraft loads prediction tool with fatigue damage analysis to aid in the development of a fatigue mitigation controller. Extensive modeling, simulation, and testing are conducted to evaluate the effectiveness of the fatigue mitigation controller and its impact on the primary flight controls to ensure that flight performance, quality, and safety are preserved.

A computer simulation using state-of-the-art models for aerodynamic loads, structural response, and an active control system was performed. It showed the possibility of significant reduction in structural stresses and hence extension of fatigue life. This is an excellent systems-level compendium of earlier government work on integrated vehicle health management and digital twin with maintenance-based design and flight.

Challenges and Opportunities

The materials work is fundamental, demonstrates significant discovery, and can be disruptive. It is discovery science. However, some work does not include all three components of theory, experiments, and modeling and simulations working closely together.

The review included an array of research on small UAS system-level assessment tools to support inserting high-fidelity modeling and expanding capability to a broader array of concepts. The platform modeling understandably does not involve scientific hypotheses, but it needs to be conceived and executed in way that will support research.

An overall approach to developing and integrating all of the various platform modeling and tools was not provided. There needs to be a tighter coupling. So what is needed is to develop a coherent strategy to ensure that the tools are appropriately connected and converging, moving in parallel toward a robust capability that supports the laboratory objectives.

A number of opportunities and challenges apply in general across the air platform tool development portfolio, and an overarching plan can address them globally. The focus on rapid UAS development at small scale, with limited research on large aircraft, may not enable the laboratory to address adequately the stated objectives to assess whether technology scales, and to explore future increments for the current large aircraft developments.

The tools do not appear to be specifically focused on decision metrics such as detection and availability. ARL needs to identify and implement improved decision metrics. Specifically, weight is not necessarily the only appropriate success metric, especially for small UASs. The UAS research needs to recognize the issues, opportunities, and constraints associated with considering the off-board ecosystem and metrics such as sustainment, transportation, storage, warfighter survivability, and supply chain. While the tools are not anticipated to include these factors, consideration of them may result in small but effective and affordable changes that can support system-level decisions.

In general, the platform modeling is not exploring disruptive or visionary component technology and approaches—for example, aero-elastically tailored tilt rotor wings. There is an opportunity to be deliberate with the tools to serve as a means to assess the value of breakthrough technologies—for example, shape memory polymers.

There has been some work to insert high-fidelity models and modules into the methodology to address the multidisciplinary system needs, but it is not a systemic objective throughout. ARL needs to consider a systematic insertion of high-fidelity modeling to capture complex behaviors. The research efforts on aerodynamics and aeromechanics needs to increase the emphasis on accounting for unsteady effects, turbulence, viscous effects, boundary layer transition, and the difficulty with multiple length and time scales. This will enable ARL to address difficult UAS questions such as unsteadiness, gusts, complex environments, and interactional aerodynamics. These will all be critical, with intent to focus on exploration of small, unique UASs in extreme conditions and environments. ARL needs to emphasize use of dynamic and nonlinear extreme problems.

The design and control developments have weak ties to, and interactions with, the platform power activity. A tighter integration with the versatile tactical power and propulsion (VICTOR) activity needs to be undertaken.

There was very limited discussion of interfacing with other Department of Defense (DoD) laboratories or industry for similar or comparable platform design tools. Correlation of the methods and tools with other stakeholders is critical to ensure trust.

The communication regarding the tools appears limited to conference papers, with very few peer-reviewed journal papers. Model validation continues to be an ad hoc process in many of the projects. Some of the efforts lack discussion of prior relevant DoD research and interactions with researchers. The system development tools in general are not embracing AI/ML/DL into the approaches.

ARL needs to consider a more robust exploration of combining design and control. For example, ARL could consider structural deformation as an opportunity for control, and combine the evaluation of planned and intentional adaptation and control authority with unplanned deformation and failures. In addition, ARL needs to leverage integration and system tools to assess value of research thrusts.

The UAS in extreme conditions such as weather, terrain/buildings, and induced disturbances especially in degraded environments (e.g., obscured, jammed, and gusty) is considered a significant area of research to pursue, as the commercial sector may not make investments to work on issues unique to the Army. ARL needs to insert considerations for extreme conditions into all research, and explore means to enable experimentation of extreme environments and conditions.

A noteworthy example of a next-generation facility that allows for experimentation with extreme environmental conditions is the unique $35 million (CAD) WindEEE wind facility at Western University in London, Ontario, in operation for several years.[2] Other more affordable facilities are available, such as the Cal Tech drone aerodynamics facility.[3] Although they are less capable, they offer the capability for testing conditions not possible in conventional wind tunnels.

Masking as a susceptibility feature is a platform consideration closely related to intelligent maneuver, so interactions with that research area need to be explored.

The focus on computational speed could be considered not just for optimizing during a nonrecurring design effort, but be used downrange for real-time configuration design adaptation, such as aggregating and disaggregating on-demand or for sustainment and degraded mode operation.

Other avenues for research could include disaggregating functions and capabilities (e.g., actuation) as is being done for platform capabilities such as swarms, machine ideation, and advanced actuation (e.g., passive and active flow control, smart materials, and plasma).

Tilt Rotor Aeroelasticity Analysis

The plan to use computational fluid dynamics (CFD) in the computations has been deferred for now. Various research groups in the national and global community have developed ROM methods for Euler and Navier-Stokes flows, and there is an opportunity to use such ROM methods in future work for this program using CFD-based computational models. In addition, the methodology developed for extracting frequency and damping of critical modes from computational data could be used for the future wind tunnel test program as well.

Stacked Rotor Aeromechanics and Acoustics

The researchers need to continue optimization studies over a greater number of independent variables and continue attempts to obtain better definition of the causative physics. In addition, the researchers need to explore the Defense Advanced Research Projects Agency (DARPA)/Bell/Boeing triple deuce stacked rotor research. In addition, the researchers need to address control dynamic response, dynamics, power plant implications, and design point and control margins, and focus on detection as the applicable metric for acoustics.

Hybrid Design and Analysis of Rotorcraft (HYDRA)

The researchers need to continue, as available machine capability allows, improving the physical fidelity. The researchers need to address structural stiffness, unsteadiness and turbulence effects of drone/drone and drone/environment interactions, and assessment of degraded modes and failures. In addition, the researchers need to consider utilizing the tool to assess the application value of ARL technologies.

UAS Transitioning Trajectory Guidance and Control

This effort is developing a simulation of the flight dynamics of a tail-sitter aircraft with low computational cost using reduced order modeling with wake-interference based on momentum theory.

[2] See https://windeee.com/, accessed August 14, 2020.
[3] See https://www.caltech.edu/research/research-facilities, accessed August 14, 2020.

The research will use high-fidelity models and experiments to identify and validate relevant vehicle constraints; derive a differentially flat, low-order trajectory planning set of equations of motion for in-flight trajectory planning; and simulate an optimized trajectory planning and controlled transition in real time. Then, additional constraints will be added such as acoustics and obstacle avoidance. The research focuses on a quadrotor biplane tail sitter to leverage data available from other ongoing research.

Based on the history of high-speed VTOL aircraft on the vertical and/or short take-off and landing (VSTOL) wheel, for which adequate control and authority through conversion and flight transition was predominantly the critical flaw, this course of research is important with the range of high-speed and long-endurance VTOL configurations.

It is important to recognize that this effort to use model-based control for optimal autonomous platform transition between flight states—more robust, smoother, quicker, more efficient, more reliable, and more predictable—is not specifically about behaviors, but about optimizing platform operation. It is also important to recognize that the transition of this capability for large-scale tail-sitter platforms needs to occur to industry platform developers.

The research focuses on a quadrotor biplane tail sitter. However, at all times the ability to expand beyond this configuration needs to be manifest. The effort needs to identify how this modeling to define a well-designed tail-sitter inner loop is extensible to enable sophisticated autonomous capabilities for a wide range of high-performance VSTOL platforms with complex dynamics.

The effort needs to move beyond just 2D trim to consider control authority in the presence of full 3D effects, transients (e.g., gusts), component dynamics, and the relevant characteristics of dynamic components.

The relationship to the HYDRA platform assessment and synthesis tool needs to be established and emphasized. In addition, the capability to use this tool to develop design guidance to inform and refine new platform designs (e.g., required downwash and wing aspect ratio combinations) needs to be considered.

The plan for wind tunnel validation is needed, to validate the use of a simple dynamics model, and model-free control.

Common Research Configuration

The plan to include flight dynamics needs to also include structural dynamics, because Group 3 aircraft are an order-of-magnitude and a half bigger than Group 2 aircraft and dynamics considerations are in play. Weight is not an appropriate success metric, especially for small-scale UASs. The research needs to include environmental conditions, especially degraded conditions such as obscured, jammed, and gusty.

Conceptual Design of UAS with Dissimilar-Size Rotors

With the concerns regarding the tool focusing specifically on rotorcraft, the transition to the National Ground Intelligence Center for use appears early and needs to be accompanied by a thorough accounting of the level of confidence in the methodology and the tool based on validation and verification. ARL needs to ascertain what organization has the authority to accredit such a tool.

The effect of the dissimilar rotors on the control system and dissimilar torque on the power plant motors and motor controllers needs to be explored, especially with the use of semi-empirical motor models. Exploring high-fidelity modeling and integration with the VICTOR activity is needed.

The impact of 3D effects and transients needs to be explored.

Sizing and Performance Tool

The researchers need to explore opportunities to include more industry participation, as a minimum in an advisory role.

Isolated pusher prop wind tunnel testing appears to consider only body effects for tares and interference, not the interactional and interference effects on the propeller model (as JBLADE does not have a body model), so there is a need to explore the effect of the body, with CFD or an empirical model. It appears that the tool selection was based on a narrow scope. No future experiments were discussed. The researchers need to continue iterating both modeling and experiment.

Automated CFD Process for Airfoil Aerodynamics Characterizations

As available machine capability increases, the researchers need to move on to additional levels of high- fidelity physics modeling to finalize optimization over the parameter space. Also, the researchers need to explore speed variations between blades and 3D effects.

Turbulence Effects on Airfoil Performance at Low Reynolds Number

This work suggests that atmospheric boundary layer turbulence will delay separation at UAS flying conditions. The literature indicates that turbulence in the atmospheric boundary layer scales with altitude and that such scales are thought to be too large to significantly delay separation at most UAS flying conditions. Therefore, further research is required to finalize to what extent atmospheric boundary layer turbulence scales will delay separation at UAS size and flying conditions. In addition, the researchers need to extend the wind tunnel studies to oscillating airfoils and to the effects of atmospheric turbulence gusts using active turbulence generation.

Reconfigurable Aero-Structures

This research explores structural adaptation using additive manufacturing to achieve span morphing of a fixed-wing UAS. The premise is that adapting the configuration can offer a unique balance of capabilities, such as long endurance of high wingspan with the capability to enter or traverse narrow spaces with short span. The stated need is a design tool to assess the relevance of adaptable structures.

There was very limited discussion of the breadth of previous similar span-morphing DoD research, and so relevant prior research needs to be reviewed.

This research is focused on generating empirical data using available resources, and has only recently begun to develop models for coupling with experiment. The research vision could be expanded beyond adaptation alone to consider how it could benefit other technologies, such as exploring bandwidth to understand capability to enhance the application of flow control.

The research is constrained by conventional engineering design perspectives, and needs to explore the impacts and opportunities with moving beyond these. For example, the challenge to achieve sufficient structural stiffness to preclude deformation could be replaced with the consideration of deformation as a means of control. In addition, the research could explore synergies of adaptation with other advanced approaches, such as flow control.

In addition to generating experimental data, the researchers need to explore theory accompanied by modeling for a robust research effort. Simulation needs to be in hand to shape and substantiate experimentation. A broader perspective on the means of construction and adaptation needs to be considered, beyond mechanical kinematics of additive manufacture for wingspan variation.

The opportunities and constraints of specific applications need to be considered, because these affect the adaptation needs and therefore feasible solutions. Notable examples are reversibility—deploy and retract yields different approaches than deployment alone—and control bandwidth (e.g., adaptive/slow versus active/rapid).

Tailorable and Multifunctional Dynamic Polymer Networks for Adaptive Structures

There was limited discussion of modeling. The research needs to ensure a balance of theory, modeling, and experimentation.

It is critical to consider fatigue properties, and the potential to extend the capability of shape memory to multiple cycles.

While the effort focuses on the polymer to perform as a self-actuated adaptive structure, a very valuable interim achievement would be a bi-modal adaptive structure that relies on external actuation, so these applications could be considered.

The promise of self-healing of the weaker chemical bonds that fail first is enticing, but the value proposition must acknowledge the design paradigm for structural materials and assemblies that fasteners and bonds need to be stronger than the substrate.

The research needs to explore a broad range of controllable stimuli to change molecular states, beyond thermal and a bit of pH, to include light and current and electromagnetics, perhaps in concert.

Non-Equilibrium Molecular Motor-Based Mechanical Actuators: Modeling the Attraction Between Two Charges in an Ionic Solution

This effort appears to be exploring from the technology side to get to an understanding of biology; it could consider also exploring the biology to get to technology.

The research could examine whether there is enough fidelity available in the experiments to use in AI/ML/DL training.

The understanding of specific phenomena—for example, non-equilibrium systems and electric double layers)—is appreciated, but the path from empiricism to deterministic models of biological actuators is unclear. There was no discussion of how, once understanding of phenomenology and science is in place, the results could turn to synthesis of capability. Ongoing research needs to emphasize the recognition that molecular mechanics requires nonreductionist multiphysics modeling.

Microstructure Deep Learning

The methodology works on data from finite element models. A major question yet to be answered is the capability to operate on experimental data.

As this research continues, it needs to consider information beyond the individual slice, in physical depth exploring 3D microstructural details, and to relate observations to changes in properties and failure mechanisms.

This small effort is appropriately pioneering a promising frontier, and while early, it needs to include application-specific metrics as possible in the research planning and execution to enhance the opportunity for transition.

The research is seeking to recognize and correlate macro material properties with observed microstructures. The research plan could address the feasibility of determining the materials and the processing required to achieving desired properties.

In addition to the nominal, universal material microstructure details, the research needs to also consider the prevalence and impact of local issues or imperfections owing to processing or other causes.

Parallelized Fluid Structure Interaction for Optimized Aero-Structural Design

In principle, the methodology can be extended to nonlinear and dynamic system responses, but the effort required is substantial. There is a significant effort in the national and global research community to address these issues, and there is an opportunity to leverage this effort.

Deep Learning of Nonlinear Dynamics from Pixel Measurements

To provide a compelling case and demonstration of the value of this approach, ultimately systems that are more complex will need to be considered. More challenging opportunities to use this approach would include inferring mathematical models for biological systems from experimental data or constructing ROMs for complex fluid systems using data from computational fluid dynamics modeling.

Computational Design and Shape Memory Polymer Actuation for Reconfigurable Aero-Structural Design

There is an opportunity for further advances in molecular dynamics (MD) simulations both by considering a wider range of material candidates and by improving the computational efficiency of the MD simulations. Reduced order modeling methods developed for fluid and macro structural systems might prove to be useful here to improve computational efficiency of the MD simulations.

Modeling and Control Methods for Future Vertical Lift Rotorcraft Fatigue Reduction

Experimental evaluation of the computer simulations is important, and such experiments are planned. The actuation method assumed may not be feasible or practical, and will limit the capability to perform experiments, so there is a need to consider the actuation approach to ensure achievability. Data from prior relevant studies could be explored, such as the Boeing Smart Materials Actuated Rotor Technology (SMART) rotor test in the NASA National Full-Scale Aerodynamics Complex 40 × 80 wind tunnel for acoustics with simple moving average actuated mid-span tabs, that was tested in both open loop and closed loop configurations.

INTELLIGENT MANEUVER

The intelligent maneuver (IM) research area focuses on fundamental research that enables effective teaming of soldiers and unmanned vehicles to conduct maneuver operations. Topics include enhancing the autonomous capabilities of unmanned systems such as global positioning system-denied navigation, agile all-terrain mobility, interaction with the environment, and advanced agent-agent and human-agent teaming concepts. This research thrust focuses exclusively on vehicle systems in real-world environments and complements research conducted within the information and computational sciences core competencies.

This assessment of the IM program is based on information presented in a set of briefings and posters prepared by the ARL team engaged in the IM research activities and associated interactions with the researchers. The panel also carefully considered supporting documents provided by the ARL. Research presented to the panel, included projects from autonomous mobility and collaborative maneuver IM areas.

Accomplishments and Advancements

In general, research presentations and posters were very well prepared and presented. These presentations, associated reports, and interactions have provided a useful and clear overview of the various projects and activities undertaken by a team of highly talented researchers engaged in a broad range of important IM projects. Researchers engaged in various IM projects were also observed to come from different stages of their careers, including individuals in the early parts of their careers, those in their mid-careers, and a good number of senior experienced individuals. This variety is a noteworthy improvement over what was observed during previous program reviews. Researchers have expertise in electrical, mechanical, and computer engineering and as well as physics, mathematics, and computational sciences. There is a renewed emphasis on enhancing experimental facilities, including a broad range of robotic platforms, multimodal sensor suites, and powerful simulation platforms as well as expanded research test areas for field studies and evaluations. IM projects include both basic research and applied research projects. Many projects have more of an applied flavor, but basic research is also being pursued. There was a good balance between theory, simulation, and experimentation, including the use of platforms. It was also evident that meaningful, long-term, and continuous engagement is maintained with academic institutions that offer expertise in key, new research topics.

Ground Mobility: An Autonomy Stack Perspective

This research is conducted as a part of the ARL intelligent unmanned ground system teaming technologies activities. The mobility stack architecture provides a carefully designed standard for effective collaboration and efficient research progress. This project has successfully engaged multiple researchers during design, development, and experimentation phases. Future field studies will allow evaluation of the key functionalities.

Reflexive Learning for Enhanced Adaptive UAS Capabilities

The tilt rotor development versus quadcopter introduces a new capability—the ability to change attitude and apply force without lateral motion. When added to a quadrotor small-unmanned aerial system (sUAS), the tilting and force capability showed promise over pure quadrotor variants, enabling a new level of control. This development offers capabilities beyond a standard UAS, potentially aiding future designs, and could lead to disruptive, game-changer functionalities. The interplay between modeling, simulation, and testing in this project was excellent.

Legged Locomotion in Resistive Terrains

This research provides a clear understanding of how to properly frame and analyze problems of legged robots traversing resistive terrain, which is realistic during practical situations. It also offered a novel framework for optimization of the cost of transport. There were exceptional contributions with significant potential and excellent use of experimental data to deduce principles of operation.

Legged Locomotion and Movement Adaptation Robotic Platform

Traversing rough terrain with an intelligent legged robot is a challenging and an important engineering and AI challenge. This project is part of a large activity involving multiple research teams.

The ARL IM team's presentation provided a very clear discussion of every aspect of the problem. The optimization of leg geometry against cost of transportation was very relevant. The team's expertise, focus, and good work ensure continued success.

Calibrating Complex Sensor Suites

Sensor calibration is a critically important and challenging task with direct influence on the success or failure of real-world problems. As numbers, types, and tasks associated with intelligent robots increase, calibration becomes that much more complicated. Calibration-related research activities at ARL IM is outstanding, and the attention to this aspect is commendable. The researchers have identified key challenges and have developed sophisticated calibration algorithms for multi-modal sensor suites. This R&D effort is rigorous, with evaluations using real-world systems. This research has definite potential to support the ultimate goal of accurate multi-modal online calibration in natural environments.

Recognition of the Role of the "Human" in Deployment of Intelligent Systems

It is refreshing to note important research undertaken in this area by a number of research teams at ARL. The following projects bring out distinctive contributions of these research activities.

Integrating Soldier-Robot Dialogue Software with ARL Autonomy Stack

Speech is a natural communication modality that allows a warfighter to command and interact with a robot with minimal training. This project is pursuing transition of the autonomous speech and dialogue processing software with the ARL robot autonomy code stack. A core component of this integration is a message bridge that handles bi-directional communication between the natural language interface and robot software.

Classification-Based Approach for Robust Warfighter-Robot Dialogue

This early-stage project presents an architecture that supports autonomous back-and-forth communications in the form of natural language dialogue between warfighters and robots. With dialogue, warfighters can issue verbal instructions to robots, while robots can provide status updates and ask for clarification. This research has good ties into the autonomy stack. The research required collection of a sizable corpus of training data on Army-specific scenarios with untrained users. This project showed a solid start on a program for systematic analysis of speech interactions between a warfighter and an intelligent robot.

After-Action Review Technology for Human-Autonomy Teaming

The global after-action review allows multi-agent—humans and autonomy—teams to review their performance and understand the outcomes of actions and decisions from a more global, top-down team perspective. This technology provides the crew with a tool to replay an operation, while identifying vehicle behaviors, weapon system and sensor behaviors, crew behaviors, specific environmental features, as well as crew/autonomy interactions. This tool will enhance teaming by supporting communication throughout the entire team, developing situation awareness, and facilitating team trust—thus providing a method for observing and evaluating context-specific, environmental, and social factors, as well as calibrating team trust in autonomy-enabled systems.

Challenges and Opportunities

The New Test Area (R2M2) is an opportunity to develop test grounds and data sets for air and ground vehicles in a variety of terrains.

In the area of human-robot communication, ARL needs to consider realistic constrains such as multiple speakers and ambient noise. In the area of human-autonomy teaming, ARL needs to consider team/crew leadership roles, both by the leader in setting the goals, and then by conducting command and control.

ARL could leverage the new test sites to generate and share standard data sets, thereby getting other groups to work on ARL-relevant problems. For example, ARL could make the mobility stack more widely usable for other groups. Sharing and wider use will also provide unique opportunities for the development of "open" data sets, performance metrics, benchmarks, and sharable modules for experimentation. These efforts will promote collaborations and would enhance research quality and productivity. It will be highly valuable if such field studies are planned and designed utilizing arrays of sensors and instrumentation to accurately capture and record states of all agents, situational dynamics, and states. This data collection will provide naturalistic data sets to develop machine learning algorithms, evaluation, and validation protocols. There needs to be more emphasis on research on intent or behavior prediction, naturalistic studies, data augmentation, annotation, transfer learning.

Other opportunities include R&D for harnessing drones (tele-operated and AI controlled) for scouting (using multi-spectral sensors), for light weapons fire, and for target designation. Given the potential complexity of sensor and intelligence inputs overwhelming field soldiers and leaders, it is necessary to harness AI/ML for targeting analysis and prioritization, as well as creating the "big picture" for enemy dispositions and operations.

Scientific research outcomes and progress needs to be carefully evaluated and needs to be reproducible by others. This need for reproducibility requires the use of appropriate metrics. The importance, utility, and criticality of performance metrics needs to be emphasized. Development of proper metrics and benchmarks, at various levels of signal, information processing, and semantic levels needs be a priority topic.

ARL leadership and program managers could address the matter of certification of autonomous systems for field operations. It is recognized that this issue appears underdeveloped, but lack of certification protocols could constrain the nature of experimentation and field trials. Emphasis on the needs and nature of the cyberspace wherein the developed systems operate is critical as a capability nears transition into the field. Recognizing the importance of cybersecurity, related considerations need to be made in the early stages of new projects—it is in general undesirable to introduce cybersecurity considerations and design modifications at the end-stage of system development. More emphasis on projects related to reliability, fault tolerance, and security at the system as well as the module level would be beneficial.

IM research pursued at ARL needs to ultimately introduce novel systems for enhanced effectiveness during end-use. These systems would naturally be composed of multiple subsystems or modules. It is necessary that a clear systems perspective in design, development, evaluation, and assessment be emphasized beyond what was provided in the presentations.

ARL needs to engage and involve the end-user into the laboratory and field activities as early as possible. In addition, ARL needs to develop and use benchmarks in guiding projects and in assessing work that is assigned to academic partners and contractors.

Research projects need to have a clear definition, justification, and characterization of success and failure of the systems, algorithms, and experiments. Failures are often just as valuable as successes, as long as there is a systematic and careful postmortem phase. Iterative refinement is thus an important guiding principle, especially in experimental research where the ability to learn from failures is key. Along these lines, it would be beneficial to researchers to lay out clearly the path to success in various projects. Questions such as those listed below could be useful in the development and assessment of research progress:

- How do the pieces fit together for robust human-robot interactions?
- How much effort will be required before modeling will be useful?
- How will results in multi-agent coordination scale to real-world applications?
- What is the path from basic research in learning Gaussian processes to real applications?

ARL needs to have more researchers publishing in high-impact factor journals and conference proceedings. Some of these papers may be published jointly with academic partners. ARL researchers need to take on primary author responsibilities. High-quality publications and associated citations are important metrics to guide scientific efforts and progress.

OVERALL QUALITY OF THE WORK

Most of the research is of high quality, but it can be further improved. The use of dimensionless numbers could be extended across all disciplines and programs, as this approach makes the results more broadly applicable. Data analytic tools could be used to analyze the large amount of data collected. Now that ARL has established collaborations with national laboratories and universities, it needs to pay attention to knowledge transfer. Fellows and early-career researchers need to be mentored to understand how their work fits in the larger picture.

Most presentations are of good quality, but they can be further improved. The presentations need to clearly articulate the objectives in quantitative terms. Some of the presentation slides were overcrowded with undersized graphics and text. Appropriate size of fonts and graphs need be used for ease of understanding. All images and graphs in the presentation could be clearly explained. The title could clearly summarize the presentation.

Platform Power

Overall, the quality of the briefings and posters in the platform power was very good. The overall research program is commendable, with high scientific quality. ARL has made remarkable progress in implementing the ARLTAB recommendations from the 2018 assessment in certain areas, such as establishing collaborative relations with universities and national laboratories in the study of ignition and combustion characteristics at altitude conditions for various fuels and fuel blends of interest. Collaborative efforts have helped improve the technical quality of the program and made use of state-of-the-art experimental facilities and models to achieve the objectives. The program now does reflect a better balance between experimental and theoretical approaches, the latter including computational efforts. ARL would now benefit from seeking to improve the in-house capabilities in these areas via interactions between ARL researchers and their collaborators.

The program on tribology and lubrication science is well formulated and aimed at understanding fundamental physics. This program has demonstrated commendable use of experimental facilities in fundamental research. Application of this capability to study the failure mechanisms for fuel pumps is an excellent application of fundamental capability in resolution of relevant problems—for example, operation using different fuels and under different atmospheric conditions.

The research program on development of coatings for austere environments addresses a very relevant problem; however, its objectives are overstated.

There were several excellent presentations by journeyman fellows and early-career researchers, clearly following the ARLTAB 2018 assessment feedback on building up the workforce pipeline.

Platform Design and Control

Overall, the platform design and control research program adds considerable value to the body of R&D knowledge. The laboratory leadership is very connected to projects, objectives, and deliverables. ARL has acted effectively to address the comments and recommendations made by ARLTAB in its 2018 assessment. ARL's focus on modeling small-scale unmanned systems is necessary to develop and employ these emerging machines, and to identify, assess, and pursue relevant breakthrough technologies.

The materials and structures research, with an emphasis on incorporating artificial intelligence (AI), machine learning (ML), and deep learning (DL), represents pioneering of complex, high-risk areas of basic research. This is demonstrating that discovery, can be disruptive, and can have wide-ranging implications for science and innovation in synthesis, and this research needs to continue. Several topics presented represent ARL's extended strategy to explore disruptive topics outside the current core competencies and to identify promising future directions for the laboratory.

While some work is not balancing theory with experiments and simulations, a particular exemplar is the microstructure deep learning that is developing AI/ML approaches by fusing simulation and experimental data. The molecular dynamics modeling in both the computational design of shape memory polymer actuation and the tailorable and multifunctional dynamic polymer networks can provide data to implement AI methods. Dynamic polymer networks research is a unique combination of morphing, self-healing, and shape memory. The non-equilibrium molecular motor research is on the leading edge of bio-hybrid basic research and will help inform ARL to shape its future portfolio.

The emerging R2C2 facility is a highlight for unmanned aerial system (UAS) experimentation, capitalizing on opportunity to offer local capability to develop autonomy for the extreme UAS vision. The nascent intelligent mechanics initiative can be disruptive, exploring the historical distinctions between pro-action and reaction, such as adaptation, reconfiguration, and control versus deformation and failure.

There are a number of talented early-career researchers who are capable in their disciplines, and they will benefit from mentoring and experience to engender a greater system-level perspective.

Intelligent Maneuver

In general, research presentations and posters were very well prepared and presented. These presentations, associated reports, and interactions have provided a useful and clear overview of the various projects and activities undertaken by a team of highly talented researchers engaged in a broad range of important IM projects. Researchers engaged in various IM projects were also observed to come from different stages of their careers including individuals in the early parts of their careers, those in their mid-careers and a good number of senior experienced individuals. This variety is a noteworthy improvement over what was observed during previous program reviews. Researchers have expertise in electrical-, mechanical-, and computer engineering and as well as physics, mathematics, and computational sciences. There is a renewed emphasis on enhancing experimental facilities including a broad range of robotic platforms, multi-modal sensor suites, and powerful simulation platforms as well as expanded research test areas for field studies and evaluations. IM projects include both basic research and applied research projects. Many projects have more of an applied flavor, but basic research is also being pursued. There was a good balance between theory, simulation, and experimentation including the use of platforms. It was also evident that meaningful, long-term, and continuous engagement is maintained with academic institutions that offer expertise in key, new research topics.

RECOMMENDATIONS

In general, the platform modeling is not exploring disruptive or visionary component technology and approaches—for example, aero elastically tailored tiltrotor wings. There is an opportunity to be deliberate with the tools to serve as a means to assess the value of breakthrough technologies—for example, shape memory polymers. ARL needs to address the potential applicability to related work in other fields, particularly in the commercial industry. While the unique challenges presented by military vehicles is recognized, at the more fundamental levels the modeling, simulation, physical tools, and physics can indeed be common between military and commercial applications, and they need to be explored further.

There has been some work to insert high-fidelity models and modules into the methodology to address the multidisciplinary systems needs, but it is not a systemic objective throughout. ARL needs to consider a systematic insertion of high-fidelity modeling to capture complex behaviors. The research efforts on aerodynamics and aeromechanics needs to increase the emphasis on accounting for unsteady effects, turbulence, viscous effects, boundary layer transition, and the difficulty with multiple length and time scales. This will enable ARL to address difficult UAS questions such as unsteadiness, gusts, complex environments, and interactional aerodynamics. These will all be critical with intent to focus on exploration of small unique UAS in extreme conditions and environments. ARL needs to emphasize use of dynamic and non-linear extreme problems.

Recommendation: The Army Research Laboratory (ARL) should consider a systematic insertion of high-fidelity modeling to capture complex behaviors. ARL should emphasize use of dynamic and non-linear extreme problems.

The tools do not appear to be specifically focused on decision metrics such as detection and availability. ARL needs to identify and implement improved decision metrics. Specifically, weight is not necessarily the only appropriate success metric, especially for small UAS. The UAS research needs to recognize the issues, opportunities, and constraints associated with considering the off-board ecosystem and metrics such as sustainment, transportation, storage, soldier survivability, and supply chain. While the tools are not anticipated to include these factors, consideration of them may result in small but effective and affordable changes that can support system-level decisions.

ARL leadership and program managers could address the matter of certification of autonomous systems for field operations. It is recognized that this issue appears underdeveloped, but lack of certification protocols could constrain the nature of experimentation and field trials. Emphasis on needs and nature of the cyberspace wherein the developed systems operate is critical as a capability nears transition into the field. Recognizing the importance of cybersecurity, related considerations need to be made in the early stages of new projects—it is in general undesirable to introduce cybersecurity considerations and design modifications at the end-stage of system development. More emphasis on projects related to reliability, fault tolerance, security, at the system as well as the module level would be beneficial.

IM research pursued at ARL need to ultimately introduce novel systems for enhanced effectiveness during end use. These systems would naturally be composed of multiple subsystems or modules. It is necessary that a clear systems perspective in design, development, evaluation, and assessment be emphasized. Systems perspective needs to include survivability and availability of the systems.

Recommendation: The Army Research Laboratory (ARL) should pursue a clear systems perspective in design, development, evaluation, and assessment including considering the eventual certification of autonomous systems by coordinating with the relevant entities for field operations, introduce cybersecurity considerations, and design modifications at the early stage of system development.

7

Crosscutting Recommendations and Exceptional Accomplishments

CROSSCUTTING RECOMMENDATIONS

The following crosscutting conclusions, recommendations, and exceptional accomplishments are based on the projects and programs presented, as a full spectrum of projects and programs within each Army Research Laboratory (ARL) research core competency and the interrelating mapping across all research core competencies' projects and programs were not provided to the Army Research Laboratory Technical Assessment Board (ARLTAB).

Four major changes to the Army and ARL clearly present challenges to all research core competencies. These are the recent Army doctrinal changes to multi-domain operations (MDO), the reorganization that put ARL under the newly formed Army Futures Command (AFC), the divestiture of 6.3 work to other organizations, and emphasis on "disruptive" technologies. Specifically, ARL has been charged with focusing on foundational research; targeting and conducting research to drive change within, across, and between disciplines; creating knowledge products for warfighting concepts; development of operating systems; and interacting with universities via the ARL Open Campus and the Army Research Office (ARO).

There is significant attention given to artificial intelligence (AI) and machine learning (ML) in research programs across different portfolios at ARL. At present, the scope of these research efforts is rather narrowly focused on technical specialty area. Fundamental research issues related to innovative ML techniques, AI implementation in resource-constrained environments, and trust and security of AI systems must still be addressed on a broader scale. It is also important to recognize that it is suboptimal to seek algorithmic advances in these areas without due consideration of hardware developments that are taking place in parallel. Given the potential of a disruptive impact of these technologies on Army operations, it is important to develop a comprehensive and integrative research plan in this emerging area. These technologies can have a transformational impact on key elements of future Army operations.

Crosscutting Recommendation 1: Activities in areas of artificial intelligence and machine learning are pervasive across Army Research Laboratory (ARL) research portfolios. ARL should emphasize the identification of a set of fundamental research questions that can provide a long-term focus for research in this area. Rich and disparate data sets collected across multiple research domains at ARL (materials, weapon systems, human-machine interactions, for example) could provide the context against which answers to these research questions are pursued.

Software development has advanced at a tremendous pace over the past few years. Much of the reason for this rapid development is the increasingly common practice of employing open source software to build software platforms. Because of this rapid pace, it will be difficult for ARL to remain competitive within the software development space. ARL needs to be a member of GitHub[1] (if it is not already), with classified information being handled appropriately.

Crosscutting Recommendation 2: The Army Research Laboratory (ARL) should develop a mechanism for collaboration between ARL and industry on software development to ensure that it continues to track the state of the art. Specifically, ARL should use and develop software platforms in collaboration with open source software libraries that will enable ARL to keep up to date and to rapidly develop software.

High-quality research cannot be pursued in a vacuum. The probability of eventual success of ARL long-range research programs will be enhanced through cognizance of outside efforts and, where appropriate, establishing formal collaborations. Establishing contacts will require, at a minimum, attendance at professional meetings and conferences and possible travel to and from leading institutions.

Crosscutting Recommendation 3: To improve career prospects of early-career researchers and improve the overall quality of the research, the Army Research Laboratory (ARL) should further encourage and facilitate all members of the research team, including junior members, to make the scientific contacts and interactions necessary to adequately place their research in the context of the entire field.

EXCEPTIONAL ACCOMPLISHMENTS

The following are the exceptional accomplishments for each core competency area.

Network and Information Sciences

The research related to imitation was found to be particularly noteworthy, drawing upon the notion that autonomous agents can learn via imitation of human "teachers," of which the Army has many. The two approaches (reinforcement learning and inverse reinforcement learning) are not new, but the research here addresses cutting-edge technology, and the results are potentially disruptive. This represents a new way to automate. The demonstration of virtual reality was also viewed positively, with the recognition that notably high-quality experience could be disruptive for situational awareness related to Army operations. ARL could leverage the platform as a test-bed for ideas such as integration of satellite perspective, multiperson teaming, and human/agent teaming, and so on.

Some research projects were considered to be exceptionally strong and offer significant potential to contribute to U.S. Army capabilities. Research related to active defense and dynamic watermarking for cyber defense of vehicles and other cyber-physical systems was one such effort where commercial vendors are unlikely to provide solutions. This significant cyber vulnerability represents a pervasive problem in most major Army vehicles.

Another noteworthy project was in the area of narrative generation as it relates to human-robot interaction. The focus of this effort was in developing an understanding and explanation of visual scenery by extracting information and adding captions to video stills that describe relevant scene information and ultimately what transpired in the sum of correlated scene(s). This result alone, if successful, could provide the warfighter a significant workload reduction in processing full-motion video or still-frame imagery.

[1] GitHub is a major open source group—see https://github.com/.

While not the focus of the ongoing work, this research could potentially also save communications bandwidth by the transmittal of the textual descriptions of the scenes instead of the full-motion video.

Computational and Atmospheric Sciences

The artificial intelligence/machine learning at the edge: inferencing engines on field programmable gate array (FPGA) project concerns development of AI/ML inference engines that can be deployed as a digital chip (application-specific integrated circuit, or ASIC) in Army environments even when network connectivity is not available (e.g., for higher precision targeting). Further, when network connectivity is regained, learning online and training could resume to further enhance target solution quality. Such an ASIC-based online/off-line device could have multiple applications across the cross-functional teams if the underlying systems design and engineering research and development (R&D) were to be successful. The technical approach involving a software framework, extensible instruction set architecture, and algorithm redesign/refactoring of convolutional neural nets (CNNs) seeks to reduce computational costs by an order of magnitude and increase efficiencies to meet space, weight, power, and time-to-solution constraints. This project spans the software-hardware space to deliver performance, portability, and programmability across multiple applications, future CNN algorithms, and future field programmable gate array (FPGA) architectures. Initial results seem encouraging, and there are many possible pathways to transition to the field while advancing the basic research. With improved direction, resources, and leveraging of related research, there is the potential for outstanding successes.

The work on improving numerical weather prediction over short time frames through assimilation of radar observations represents innovative research in support of an impactful real-world application and is especially noteworthy. ARL—collaborating with the Combat Capabilities Development Command (CCDC) Aviation and Missile Center, formerly known as AMRDEC—is developing a new mesoscale modeling capability that will provide forecasts in data-sparse regions such as the test facility on Kwajalein Atoll in the Pacific Ocean. Owing to the site's unique remote location, current Department of Defense (DoD) weather capabilities cannot meet these needs. The ARL approach assimilates radar observations already available at the location into the widely used weather research and forecasting (WRF) prediction model. Radar measurements of reflectivity are then used to infer rates of latent heating for input to WRF. Assessments of the new modeling capability demonstrate increases in probability of correct prediction of weather phenomena through assimilation of radar data by factors up to one order of magnitude.

Human Sciences

ARL has developed robust, contextualized human-autonomy teaming research laboratories, and has developed state-of-the-art synthetic task environments and data collection platforms through Cyber-Human Integrated Modeling and Experimentation Range Army (CHIMERA) and Information for Mixed Squads Laboratory (INFORMS). INFORMS has the potential to gather data that do not exist anywhere else on platoon-size teams. This could lead to very interesting science on platoon-size interactions, shared mental models, and attention allocation. In addition, the CHIMERA laboratory has outstanding metrics collection capabilities for cyber-human systems studies. ARL has significant experience and investment in neurophysiological measures to infer human states, as well as instrumented laboratories and simulation capabilities. Such advanced facilities promise to provide the ecological validity and experimental control needed to generate empirical evidence to address critical research questions and advance the science of human-technology integration.

A significant achievement includes the collection and management of large data sets. Ambitious data collection activities—over time, between and within subjects, in the field—with target populations have created a number of large data sets that will be used to drive ML and simulation. The team has access to good information technology infrastructure to store and protect these organized and time-stamped infrastructure components. These researchers are pioneering something new.

The group has established a unique and valuable niche for engineering advances for neurophysiological monitoring in dynamic tasks, such as ambulatory electroencephalogram (EEG) and eye-gaze tracking. Specific contributions include novel algorithms for achieving accurate, reliable, and online detection of evoked response signals in the EEG while subjects are engaged in complex, operationally relevant activities. The group has also made novel contributions to the hardware and software technologies for EEG monitoring, particularly in mobile scenarios, which are prone to contamination from motion and environmental noise sources. The group has taken a rigorous approach to addressing these problems, developing a novel test-bed for isolating and eliminating sources of noise through innovative electrode and signal processing strategies. The group has also created unique testing platforms for studying human performance in complex tasks involving teaming among groups of humans and autonomous vehicles in ecologically valid settings. These platforms are generating data sets that are unique and exceedingly rich in measuring physiological and behavioral aspects of human performance, spanning multiple time scales and modalities. In addition to supporting immediate questions, these data sets could be leveraged to support secondary analyses within and beyond ARL.

Materials and Manufacturing Sciences

The advanced solid-state lasers group continues to be one of the “crown jewels” for ARL by driving infrared laser technology with the recent achievement of lasing at 3 microns in new, low phonon energy hosts such as barium fluoride and yttrium lithium fluoride. The sensor protection scientific team is commended for the clever iridium chemistry that is being pursued to develop broadband reverse saturable absorption materials and the GMR filters. Among the impressive accomplishments of the integrated photonics research team is the dramatic improvement in the performance of optical frequency combs and the successful demonstration of electrically steerable phased arrays.

The scientific quality of the work in diamond electronics is excellent and makes a significant contribution to the field. The effort is currently focused on improving device performance by introducing transition metal oxides or boron nitride to stabilize the diamond surface. The group has achieved state-of-the-art direct current (DC) characteristics utilizing solid oxide cap layers. ARL has an impressive development of two important optical power device types for the Army—the improvement and standardization of high-voltage power devices and the creation of UV emitters and detectors for covert communications and sensing. All the work is on optical power devices is of high technical quality comparable to the best peer laboratories.

The team working on aqueous lithium-ion battery (LIB) materials and systems is making exceptional advancements in the science and technology (S&T) of electrical energy storage with lithium-ion batteries. Aqueous electrolytes are nonflammable and thus dramatically safer than conventional electrolytes for military use. This ARL team has advanced the science of ultra-concentrated aqueous electrolytes that has enabled the use of high-voltage electrodes that previously were incompatible with aqueous systems. Work by the ARL team spans a broad range from computational modeling of interfacial chemistry to fabrication of cells of a size (approximately 5 Ah) suitable for field use. This is a wide range of activity for a relatively small group that has deservedly garnered positive international recognition. Work on wireless energy transmission is also making excellent progress with capabilities, for local wireless energy transmission (centimeters to meters) using electronic and acoustical waves, and is among the best in the world.

Propulsion Sciences

The program on tribology and lubrication science is well formulated and aimed at understanding fundamental physics. This program has demonstrated commendable use of experimental facilities in fundamental research. Application of this capability to study the failure mechanisms for fuel pumps is an excellent application of fundamental capability in resolution of relevant problems—for example, operation using different fuels and under different atmospheric conditions.

A particular exemplar is the microstructure deep learning (DL) that is developing AI/ML approaches by fusing simulation and experimental data. The molecular dynamics modeling in both the computational design of shape memory polymer actuation and the tailorable and multifunctional dynamic polymer networks can provide data to implement AI methods. Dynamic polymer networks research is a unique combination of morphing, self-healing, and shape memory. The non-equilibrium molecular motor research is on the leading edge of bio-hybrid basic research and will help inform ARL to shape its future portfolio.

The tilt rotor development versus quadcopter introduces a new capability—the ability to change attitude and apply force without lateral motion. When added to a quadrotor small-unmanned aerial system (sUAS), the tilting and force capability showed promise over pure quadrotor variants, enabling a new level of control. This development offers capabilities beyond a standard UAS, potentially aiding future designs, and could lead to disruptive, game-changer functionalities. The interplay between modeling, simulation, and testing in this project was excellent.

Appendixes

A

Army Research Laboratory Organization and Research Core Competency Clusters

Figure A.1 is an organization chart for the Army Research Laboratory (ARL), and Table A.1 maps the ARL organizational chart to the research core competencies reviewed in 2019 and 2020.

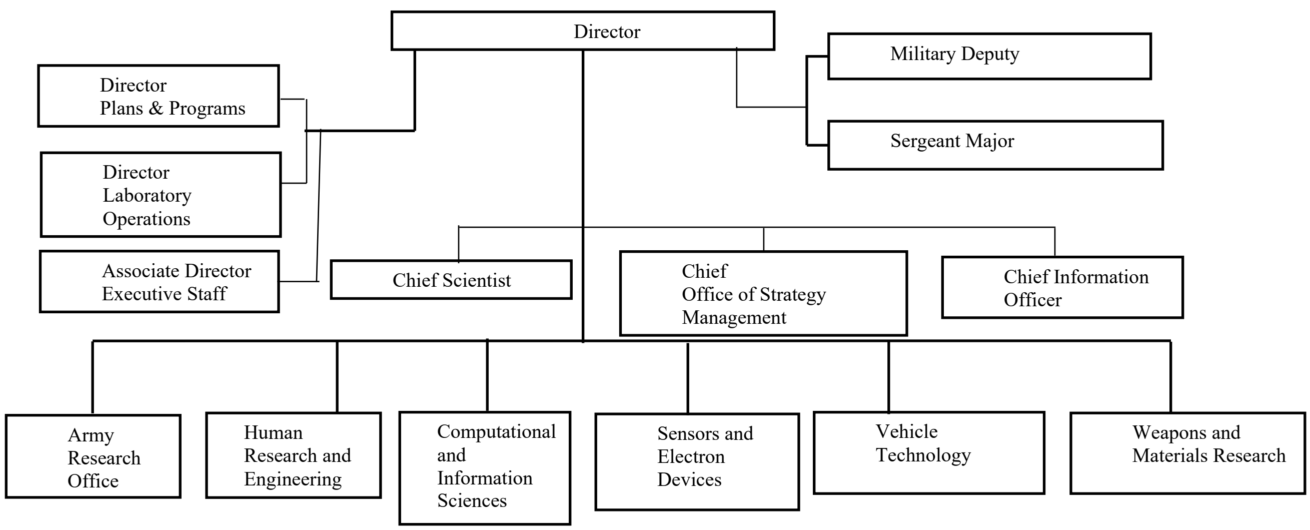

FIGURE A.1 Army Research Laboratory organization chart.

TABLE A.1 Mapping of the Army Research Laboratory (ARL) Organization Chart to the Research Core Competency Areas Reviewed in 2019 and 2020

Research Core Competency	Topic	ARL Directorate Involved
2019		
Network and Information Sciences	Information Sciences Networks Cyber	CISD, SEDD, HRED
Computational Sciences	Computational Sciences Atmospheric Sciences	CISD, SEDD, VTD, WMRD
Human Sciences	Human-Autonomy Team Interactions and Humans Understanding Autonomy Autonomy Understanding Humans and Estimating Human-Autonomy Team Outcomes Human Interest Detection Cyber Science and Kinesiology Neuroscience, Training Effectiveness, and STRONG	HRED, CISD, VTD
2020		
Materials and Manufacturing Sciences	Optical Sciences and Photonics Electronics and Optoelectronics Energy Science	SEDD, WMRD
Propulsion Sciences	Platform Power Platform Design and Control Intelligent Maneuver	VTD, CISD, SEDD, HRED

NOTE: CISD, Computational and Information Sciences Directorate; HRED, Human Research and Engineering Directorate; SEDD, Sensors and Electron Devices Directorate; VTD, Vehicle Technology Directorate; and WMRD, Weapons and Materials Research Directorate.

B

Army Research Laboratory Technical Assessment Board Members and Staff Biographical Information

JENNIE S. HWANG, *Chair*, is CEO of H-Technologies Group and a Board Trustee at Case Western Reserve University. Dr. Hwang's career encompasses corporate and entrepreneurial businesses, innovative research, advanced manufacturing, technology transfer and global leadership positions, as well as corporate and university governance. She is the author of 650+ publications/editorials and several internationally used textbooks. Among her many honors/awards are Congressional Certificates of Achievement & Recognition; induction into International Hall of Fame—Women in Technology; named the R&D-Stars-to-Watch; Ohio Women Hall of Fame; Distinguished Alumni Awards; Honorary Doctoral degree; and YWCA Achievement Award. Dr. Hwang was the CEO of International Electronic Materials Corp. and has held senior executive positions with Lockheed Martin Corp., Hanson, PLC, and Sherwin-Williams Co. and co-founded entrepreneurial businesses. Internationally recognized as a pioneer and long-standing leader in the interconnecting electronic materials, electronics miniaturization, and advanced manufacturing, she has served as global president of the Surface Mount Technology Association and in other global leadership positions. An international speaker, Dr. Hwang has lectured to tens of thousands of managers, engineers, and researchers on emerging technologies and advanced manufacturing via professional development courses. Her speeches range from university commencement addresses to the keynote at DoD Federal Women's Program to tutorials at the U.S. Patent and Trademark Office. She is also a prolific author and speaker on education, workforce, and social and business issues. Additionally, Dr. Hwang has served as a board director for Fortune 500 NYSE-traded and private companies and various university and civic boards (e.g., International Advisory Board of the Singapore Advanced Technology and Manufacturing Institute and a number of international industry boards). At the National Academies, Dr. Hwang has served as the NAE Membership Search Executive and Chair of Peer Committee (Materials Section), National Materials and Manufacturing Board, Army Science and Technology Board, NIST Technical Assessment Board and Panels, DoD R&D Globalization Board, Committee on Forecasting Future Disruptive Technologies, Diversity Forum, and NAE Award Committee, among others. She also chaired the Board on Army RDT&E, Systems Acquisition, and Logistics and chairs the Technical Assessment Board of Army Research Laboratory. Her formal education includes Harvard University Executive Program, Columbia University Business School Governance Program, and four academic degrees (Ph.D., M.A., M.S., B.S.) in materials science and engineering, chemistry, and liquid crystal science. The Dr. Jennie S. Hwang Award for Faculty Excellence was established at her alma maters. The Dr. Jennie S. Hwang YWCA Award is established in her honor, now for 20 years running, to encourage and recognize outstanding women students in STEM. The Dr. Jennie S. Hwang Endeavor Fund, an endowment at NAE, funds programs that support high school and college students—with a preference for women and underrepresented minorities—to enhance exposure to diverse and/or international perspectives in engineering education, networking, and the profession. For further information, see www.JennieHwang.com.

FREDERICK R. CHANG is the chair of the Computer Science Department in the Lyle School of Engineering at Southern Methodist University (SMU). Dr. Chang is also the executive director of the Darwin Deason Institute for Cyber Security, the Bobby B. Lyle Endowed Centennial Distinguished Chair in Cyber Security, and a professor in the Department of Computer Science. He is a senior fellow in the John Goodwin Tower Center for Political Studies in SMU's Dedman College. Additionally, Dr. Chang's career spans service in the private sector and in government including as the former director of research at the National Security Agency. Dr. Chang was elected as a member of the National Academy of Engineering in 2016. He is currently the co-chair of the Intelligence Community Studies Board of the National Academies of Sciences, Engineering, and Medicine, and he is also a member of the Army Research Laboratory Technical Assessment Board. Dr. Chang has served as a member of the Computer Science and Telecommunications Board of the National Academies and as a member of the Commission on Cybersecurity for the 44th Presidency. He is the lead inventor on two U.S. patents and has appeared before Congress as a cybersecurity expert witness on multiple occasions. Dr. Chang received his B.A. degree from the University of California, San Diego, and his M.A. and Ph.D. degrees from the University of Oregon. He has also completed the Program for Senior Executives at the Sloan School of Management at the Massachusetts Institute of Technology. He has been awarded the National Security Agency Director's Distinguished Service Medal.

MARK E. EBERHART is a professor in the Department of Chemistry and Geochemistry at the Colorado School of Mines, where he directs the Molecular Theory Group (MTG). At the MTG, knowledge of bonding is obtained through detailed topological analyses of the spatial distribution of electrons in molecules and solids. Many subtle aspects of the distribution become obvious when viewed from a topological perspective. The accompanying topological formalism gives well-defined, unambiguous, meaningful and consistent definitions to previously indeterminate quantities such as atomic bonds and basins. Dr. Eberhart's work is based primarily on first principles computations, which provide the electron charge densities, and topological analysis software developed at the MTG. He is also exploring the topological and geometric origins responsible for the stability of amorphous metallic alloys. In addition to his work on condensed phase systems, his group has active research programs exploring the relationships between charge density and the chemical properties of molecular systems, both organic and inorganic. Dr. Eberhart holds a B.S. degree in chemistry and applied mathematics from the University of Colorado, an M.S. degree in physical biochemistry from the University of Colorado, and a Ph.D. in materials science and engineering from the Massachusetts Institute of Technology.

PRABHAT HAJELA is provost and professor of mechanical and aerospace engineering at the Rensselaer Polytechnic Institute. Dr. Hajela's research interests include analysis and design optimization of multidisciplinary systems, system reliability, emergent computing paradigms for design, artificial intelligence, and machine learning in multidisciplinary analysis and design. Before joining Rensselaer, he worked as a research fellow at the University of California, Los Angeles, for a year, and was on the faculty at the University of Florida for 7 years. Dr. Hajela has conducted research at NASA's Langley and Glenn Research Centers, and at the Eglin Air Force Armament Laboratory. In 2003, Dr. Hajela served as a Congressional Fellow responsible for Science and Technology Policy in the Office of U.S. Senator Conrad Burns (R-MT). He worked on several legislative issues related to aerospace and telecommunications policy, including the anti-SPAM legislation that was signed into law in December 2003. Dr. Hajela is a fellow of the American Institute of Aeronautics and Astronautics (AIAA), a fellow of the Aeronautical Society of India (AeSI), and a fellow of the American Society of Mechanical Engineers (ASME). He has held many editorial assignments, including editor of *Evolutionary Optimization* and associate editor of the *AIAA Journal*, and is on the editorial board of six other international journals. He has published more than 270 papers and articles in the areas of structural and multidisciplinary optimization, and is an author or co-author of four books in these areas. In 2004, Dr. Hajela was the recipient of AIAA's Biennial Multidisciplinary Design Optimization Award.

JAMES S. HARRIS is the James and Ellenor Chesebrough Professor Emeritus in the School of Engineering at Stanford University. Prior to joining the Stanford Department of Electrical Engineering in 1982, Dr. Harris was with Rockwell International Science Center, where he held various positions, from technical staff member to director of optoelectronics research. His major interest is to use molecular beam epitaxy (MBE) to produce unique materials. The growth of such unique combinations of materials enables quantum-size effects to create entirely new device structures based on tunneling electron spin and transitions between quantum states. Most recently, Dr. Harris has applied this technology to incorporate photonic crystal and plasmonic structures to produce an integrated biofluorescence sensor that has been implanted into mice to study cancer development and therapies. He is a fellow of IEEE, the American Physical Society, and the Optical Society of America. In 2000, Dr. Harris received the IEEE Third Millennium Medal. In 2011, he was elected to the NAE "for contributions to epitaxial growth of compound semiconductor materials and their applications." In 2013, he received the Aristotle Award from the Semiconductor Research Corporation. In 2014, he received the Alfred Y. Cho MBE Award at the International MBE Conference. Dr. Harris received his B.S. (1964), M.S. (1965), and Ph.D. (1969) in electrical engineering from Stanford University.

WESLEY L. HARRIS is the Charles Stark Draper Professor of Aeronautics and Astronautics and director of the Lean Sustainment Initiative at the Massachusetts Institute of Technology. Dr. Harris was elected to the National Academy of Engineering "for contributions to understanding of helicopter rotor noise, for encouragement of minorities in engineering, and for service to the aeronautical industry." He has performed research and published in refereed journals in the following areas: fluid mechanics; aerodynamics; unsteady, nonlinear aerodynamics; acoustics; lean manufacturing processes; and military logistics and sustainment. Dr. Harris has substantial experience as a leader in higher education administration and management. He also has demonstrated outstanding leadership in managing major national and international aeronautical and aviation programs and personnel in the executive branch of the federal government. He is an elected fellow of the AIAA, AHS, and NTA for personal engineering achievements, engineering education, management, and advancing cultural diversity.

WILLIAM S. MARRAS is the Honda Chair Professor in the Department of Integrated Systems Engineering at Ohio State University, and holds joint appointments in the Departments of Orthopedic Surgery, Physical Medicine, and Neurosurgery. Dr. Marras is also the executive director and scientific director of the Spine Research Institute and the executive director of the Institute for Ergonomics. His research is centered on understanding the role of biomechanics in spine disorder causation and its role in the prevention, evaluation, and treatment of spine disorders. Dr. Marras's research includes epidemiologic studies, laboratory biomechanics studies, mathematical modeling, and clinical studies. His findings have been published in more than 200 peer-reviewed journal articles and have been cited more than 15,000 times. Dr. Marras also has written numerous books and book chapters, including his most recent book titled *The Working Back: A Systems View*. He holds fellow status in six professional societies including the American Society for the Advancement of Science (AAAS) and has been widely recognized for his contributions through numerous national and international awards, including two Volvo Awards for Low Back Pain Research. Dr. Marras has been active in the National Academies, having served on over a dozen boards and committees, and has served as chair of the Board on Human Systems Integration for multiple terms. He has also served as editor-in-chief of *Human Factors* and is currently deputy editor of *Spine* and is the immediate past president of the Human Factors and Ergonomics Society. Dr. Marras recorded a TEDx talk titled "Back Pain and Your Brain" and was recently featured on NPR's *All Things Considered*. He received a B.S. in engineering from Wright State University, an M.S. in industrial engineering from Wayne State University, a Ph.D. in bioengineering and ergonomics from Wayne State University, and a D.Sc. Honoris Causa from the University of Waterloo.

DANIEL A. REED was named the senior vice president for academic affairs at the University of Utah in April 2019. Dr. Reed is the past vice president for research and economic development at the University of Iowa. He was also the University Computational Science and Bioinformatics chair, and professor of computer science and electrical and computer engineering. Dr. Reed was corporate vice president at Microsoft from 2009-2012, responsible for global technology policy and extreme computing, and director of scalable and multicore computing at Microsoft from 2007 until 2009. He founded the Renaissance Computing Institute in 2004 and served as its director until December 2007. Dr. Reed was also Chancellor's Eminent Professor and served as senior advisor for strategy and innovation to Chancellor James Moeser, University of North Carolina (UNC), Chapel Hill. He served as CIO and vice chancellor for information technology services at UNC, Chapel Hill, from June 2004 through April 2007. Prior to that, Dr. Reed was director of the National Center for Supercomputing Applications (NCSA), and Gutgsell Professor and head of the Department of Computer Science at the University of Illinois, Urbana-Champaign. He was appointed to the President's Council of Advisors on Science and Technology (PCAST), by President George W. Bush, in 2006 and served on the President's Information Technology Advisory Committee (PITAC) from 2003-2005. As chair of PITAC's computational science subcommittee, Dr. Reed was lead author of the report *Computational Science: Ensuring America's Competitiveness*. On PCAST, he co-chaired the Networking and Information Technology subcommittee (with George Scalise of the Semiconductor Industry Association) and co-authored a report on the Networking and Information Technology Research and Development (NITRD) program called *Leadership Under Challenge: Information Technology R&D in a Competitive World*. He is also a member of PCAST's Personalized Medicine subcommittee. Dr. Reed is the past chair of the board of directors of the Computing Research Association (CRA) and currently serves on its Government Affairs Committee. CRA represents the research interests of the university, national laboratory, and industrial research laboratory communities in computing across North America. Dr. Reed received his B.S. (summa cum laude) in computer science from the University of Missouri, Rolla, in 1978, and his M.S. and Ph.D. in computer science from Purdue University in 1980 and 1983.

LESLIE E. SMITH is scientist emeritus at the National Institute of Standards and Technology (NIST) after retiring as director of the Materials Science and Engineering Laboratory. Dr. Smith was previously chief of the Polymers Division at NIST, where he built a world-class scientific program in polymer science that has made both fundamental advances to science and significant contributions to industrial technology. His personal research interests have been in the absorption of polymers and biological polymers relevant to artificial vascular materials and degradation reactions of polyesters, primarily as related to the lifetime of magnetic storage media. Dr. Smith has also edited a number of professional reference books. His external positions have included U.S. editor, *Polymer Communications*; member, Advisory Committee on Preservation, National Archives; Advisory Board for Polymer Programs, University of Connecticut; Council for Polymer Science and Engineering, University of Akron; chair, Materials Technology Subcommittee, NSTC, OSTP; and member, Board of Directors ASTM International.

DAVID A. WEITZ is the Mallinckrodt Professor of Physics and Applied Physics at Harvard University in the John A. Paulson School of Engineering and Applied Science (SEAS). Dr. Weitz is also the director of the Materials Research Science and Engineering Center (MRSEC), the co-director of the BASF Advanced Research Initiative, a core faculty member of the Wyss Institute for Biologically Inspired Engineering, and a member of the Kavli Institute for Bionano Science and Technology. At Harvard University, Dr. Weitz's research interests are the physics of soft condensed matter, specifically their structural and mechanical properties, the properties of colloidal suspensions, the mechanical properties of biomaterials, and microfluidics for making emulsions using multiphase flow. He also works closely with industry, having served on the board of directors for several start-ups including microfluidics-driven startups GnuBIO and Raindance. Dr. Weitz has served as associate editor and member on the *Proceedings of the National Academy of Sciences* editorial board, was a member of the National Academies Panel on Review of the Physical Measurement Laboratory at the National Institute of Standards and Technology, and was a chair on the Condensed Matter and Materials Research Committee. Dr. Weitz has served as a member of the National Academies standing Committee on Biological and Physical Sciences in Space. Dr. Weitz earned his B.Sc. with honors in physics in 1973 from the

University of Waterloo, his A.M. in physics in 1975 from Harvard University, and his Ph.D. in physics, also from Harvard University.

Staff

AZEB GETACHEW is a senior program assistant at the Laboratory Assessments Board (LAB). Ms. Getachew joined the LAB in March 2017 and is responsible for administrative and logistical planning for project meetings and other activities. She previously worked as an interim administrative assistant in several administrative capacities at the National Academies including the LAB, the Naval Studies Board, and the Institute of Medicine. Ms. Getachew has an associate of applied science degree in information systems from Columbia Union College, which is now Washington Adventist University.

EVA LABRE is the administrative coordinator for the LAB. Since 2009, Ms. Labre has been responsible for assisting in the management of the administrative aspects of panel formation, panel meetings, report publication and dissemination, and program development. In addition, she has been responsible for travel expense accounting. In 2014, she was promoted and has recently taken on more responsibilities related to financial aspects of the work of the LAB. Ms. Labre previously held administrative positions at the National Academies on the staff of the Committee on International Organizations and Programs in the Office of International Affairs and on the staff of the Research Associateship Program in the Office of Scientific and Engineering Personnel. Ms. Labre has a B.A. in art history from George Washington University.

JAMES P. MCGEE is the director of the LAB, the Army Research Laboratory Technical Assessment Board (ARLTAB), and the Committee on the National Institute of Standards and Technology (NIST) Technical Programs, all within the Division on Engineering and Physical Sciences (DEPS) at the National Academies. Since 1994, Dr. McGee has been a senior staff officer at the National Academies, directing projects in the areas of systems engineering and applied psychology, including activities of the ARLTAB and projects of the Committee on National Statistics' Panel on Operational Testing and Evaluation of the Stryker Vehicle and the Committee on Assessing the National Science Foundation's Scientists and Engineers Statistical Data System, the Committee on the Health and Safety Needs of Older Workers, and the Steering Committee on Differential Susceptibility of Older Persons to Environmental Hazards. He has also served as staff officer for the National Academies projects on air traffic control automation, musculoskeletal disorders and the workplace, and the changing nature of work. Prior to joining the National Academies, Dr. McGee held technical and management positions in systems engineering and applied psychology at IBM, General Electric, RCA, General Dynamics, and United Technologies. He received his B.A. from Princeton University and his Ph.D. from Fordham University, both in psychology, and for several years instructed postsecondary courses in applied psychology and in organizational management.

ARUL MOZHI is senior program officer at the LAB. Since 1999, Dr. Mozhi has been directing projects in the areas of defense science and technology, including those carried out by numerous study committees of the LAB, the ARLTAB, the Naval Studies Board, the Air Force Studies Board, the Aeronautics and Space Engineering Board, and the National Materials and Manufacturing Board. Prior to joining the National Academies, Dr. Mozhi held technical and management positions in systems engineering and applied materials research and development at UTRON, Roy F. Weston, and Marko Materials. He received his M.S. and Ph.D. degrees (the latter in 1986) in materials engineering from Ohio State University and then served as a postdoctoral research associate there. He received his B.Tech. in metallurgical engineering from the Indian Institute of Technology, Kanpur, in 1982.

C

Assessment Criteria

The Army Research Laboratory Technical Assessment Board (ARLTAB) assessment considered the following general questions posed by the Army Research Laboratory (ARL) director:

- Is the scientific quality of the research of comparable technical quality to that executed in leading federal, university, and industrial laboratories both nationally and internationally?
- Does the research program reflect a broad understanding of the underlying science and research conducted elsewhere?
- Does the research employ the appropriate laboratory equipment and numerical models?
- Are the qualifications or the research team compatible with the research challenge?
- Are the facilities and laboratory equipment state of the art?
- Are programs crafted to employ the appropriate mix of theory, computation, and experimentation?

To assist ARL in addressing promising technical approaches, the board also considered the following questions:

- Are there especially promising projects that, with improved direction or resources, could produce outstanding results that can be transitioned ultimately to the field?
- Are there promising outside-the-box concepts that should be pursued but are not currently in the ARL portfolio?

The ARLTAB applied the following metrics or criteria to the assessment of the scientific and technical work reviewed at ARL:

Project Goals and Plans

- Are the objectives clearly stated and are tasks well defined to achieve objectives?
- Are milestones defined? Are they appropriate? Do they appear feasible?
- Are obstacles and challenges defined (technical, resources, time)?
- Assuming success, what difference will it make to the science base, to the end user, or in a mission area context?
- Does the project plan identify dependencies (i.e., successes depend on success of other activities within the project or on the success of projects developed outside ARL)?
- Does the project represent an area where application of ARL strengths is appropriate?
- What stopping rules, if any, are being or should be applied?

Methodology and Approach

- Are the methods (e.g., laboratory experiment, modeling/simulation, field test, analysis) appropriate to the problems? Do these methods integrate?
- Are the hypotheses appropriately framed within the literature and theoretical context?
- Is there an alternative approach that facilitates the progress of the project?
- Is there a clearly identified and appropriate process for performing required analyses, prototypes, models, simulations, tests, and so on?
- Is the data collection and analysis methodology appropriate?
- Are conclusions supported by the results?
- Are proposed ideas for further study reasonable?
- Do the trade-offs between risk and potential gain appear reasonable?
- If the project demands technological or technical innovation, is that occurring?

Capabilities and Resources

- If staff or equipment is not adequate, how might the project be triaged (which technical thrust should be emphasized, which sacrificed?) to best move toward its stated objectives?
- Will the project recruit new talent into ARL?

Scientific Community

- Presentations and colloquia.
- Participation in professional activities (society officers, conference committees, journal editors).
- Papers in quality refereed journals and conference proceedings (and their citation index).
- Educational outreach (serving on graduate committees, teaching/lecturing, invited talks, mentoring students).
- Fellowships and awards (external and internal).
- Participation on review panels (Army Research Office, National Science Foundation, Multidisciplinary University Research Initiative, etc.).
- Patents and intellectual property and examples of how the patent or intellectual property is used.
- Involvement in building an ARL-wide cross-directorate community.
- Public recognition—for example, in the press and elsewhere—for ARL research.
- Collaborations (lead, partner, support).

D

Acronyms

1D	one-dimensional
2D	two-dimensional
2PA	two-photon absorption
3D	three-dimensional
ABL	atmospheric boundary layer
ABLE	atmospheric boundary layer environment
ACT-R	adaptive control of thought—rational
ACT-RN	adaptive control of thought—rational neuro
AFC	Army Futures Command
AI	artificial intelligence
ALE	air launched effect
ALP	aeroelastic lumped parameter
ANL	Argonne National Laboratory
A-PNT	assured positioning, navigation, and timing
ARL	Army Research Laboratory
ARLTAB	Army Research Laboratory Technical Assessment Board
ARO	Army Research Office
AR/VR	augmented and virtual reality
ASIC	application-specific integrated circuit
BED	Battlefield Environments Division
C4ISR	command, control, communications, computers, intelligence, surveillance, and reconnaissance
Cal Tech	California Institute of Technology
CCDC	Combat Capabilities Development Command
CFD	computational fluid dynamics
CHIMERA	Cyber-Human Integrated Modeling and Experimentation Range Army
CISD	Computational and Information Sciences Directorate
CIWS	Corridor Integrated Weather System
CMF	Cyber Mission Force
CMU	Carnegie Mellon University
CNN	convolutional neural net
CPT	cyber protection team
CRA	Collaborative Research Alliance
CRADA	Cooperative Research and Development Agreement
CRC	common research configuration
CTA	Collaborative Technology Alliance

CTA	concepts, trades, and analyses
CW	continuous wave
DARPA	Defense Advanced Research Projects Agency
Deep TAMER	Deep Training an Agent Manually via Evaluative Reinforcement
DL	deep learning
DoD	Department of Defense
DOE	Department of Energy
EEG	electroencephalogram
ENZ	epsilon-near-zero
EPA	Environmental Protection Agency
E-PIC	electronic/photonic integrated circuit
ERA	essential research area
EW	electronic warfare
FE	finite element
FEA	finite element analysis
FOM	Figure of Merit
FSR	free-spectral range
FPGA	field programmable gate array
FY	fiscal year
GMR	guided-mode resonance
GPS	global positioning system
HDR	high dynamic range
HFM	high-fidelity model
HID	human interest detection
HMS	hierarchical multiscale
HPC	high-performance computing
HRED	Human Research and Engineering Directorate
HS	human sciences
HYDRA	Hybrid Design and Analysis of Rotorcraft
IM	intelligent maneuver
INFORMS	Information for Mixed Squads Laboratory
IPN	interpenetrating network
IS	information sciences
ITO	indium tin oxide
LAB	Laboratory Assessments Board
LBM	lattice-Boltzmann method
LfD	Learning from Demonstration
LFM	low-fidelity model
LIB	lithium-ion battery
LWIR	long-wave infrared
MD	molecular dynamics
MDO	multi-domain operations
MEMS	microelectromechanical system

ML	machine learning
MOUT	Military Operations in Urban Terrain
MSA	meteorological sensor array
MWIR	medium-wave infrared
NASA	National Aeronautics and Space Administration
NEEC	nuclear excitation by electron capture
NIST	National Institute of Standards and Technology
NRL	Naval Research Laboratory
NWP	numerical weather prediction
OER	oxygen evolution reaction
OPLAN	operational plan
PCM	phase change material
PI	principal investigator
PIC	photonic integrated circuit
PP	predictive processing
QIS	quantum information science
R&D	research and development
RDT&E	research, development, test, and evaluation
RF	radio frequency
RI	radio isotope
ROC	receiver operating characteristic
ROM	reduced order model
RSA	reverse saturable absorption
S&E	scientist and engineer
S&T	science and technology
SA	saturable absorber
SDR	standard dynamic range
SEDD	Sensors and Electron Devices Directorate
SiC	silicon carbide
SNL	Sandia National Laboratory
STRONG	strengthening teamwork for robust operations with novel groups
sUAS	small-unmanned aerial system
SWaP-C	size, weight, and power as well as cost
SWIR	short-wave infrared
TAMU	Texas A&M University
TPV	thermal photovoltaic
UAS	unmanned aerial system
UAV	unmanned aerial vehicle
VICTOR	versatile tactical power and propulsion
VHF	very high frequency
VTD	Vehicle Technology Directorate
VSTOL	vertical and/or short take-off and landing

VTOL	vertical take-off and landing
WMRD	Weapons and Materials Research Directorate
WRF	weather research and forecasting
WSMR	White Sands Missile Range
YSZ	yttrium stabilized zirconia