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CONTRIBUTORS

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ASSESSMENT OF THE ARMY RESEARCH LABORATORY: INTERIM REPORT

Army Research Laboratory Technical Assessment Board

Laboratory Assessments Board

Division on Engineering and Physical Sciences

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[2] Member of the National Academy of Sciences.

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Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for 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 wish to thank the following individuals for their review of this report:

Ross B. Corotis, NAE, University of Colorado, Boulder,
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Richard M. Murray, NAE, California Institute of Technology,
Michael Posner, NAS/IOM, University of Oregon,
Edgar A. Starke, Jr., NAE, University of Virginia, and
Dwight C. Streit, NAE, University of California, Los Angeles.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Louis J. Lanzerotti, NAE, New Jersey Institute of Technology. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring board and the institution.

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APPENDIXES

Summary

The charge of the Army Research Laboratory Technical Assessment Board (ARLTAB) is to provide biennial assessments of the scientific and technical quality of the research, development, and analysis programs at the Army Research Laboratory (ARL). The ARLTAB is assisted by five panels, each of which focuses on the portion of the ARL program conducted in one of ARL's core technical competencies: ballistics sciences, human sciences, information sciences, materials sciences, and mechanical sciences. When requested to do so by ARL, the ARLTAB also examines plans for new work that ARL may initiate.

This interim report summarizes the findings of the Board for the first year of this biennial assessment. During the first year the Board examined the following elements within the ARL competency areas: within ballistic sciences, terminal ballistics; within human sciences, translational neuroscience and soldier simulation and training technology; within information sciences, autonomous systems; and within materials sciences, energy materials and devices, photonic materials and devices, and biomaterials. The review of autonomous systems included examination of the mechanical sciences competency area for autonomous systems. A second, final report will subsume the findings of this interim report and add the findings from the second year of the review, during which the Board will examine additional elements within the five ARL competency areas.

BALLISTICS SCIENCES: TERMINAL BALLISTICS

ARL has a strong record of achievement and timely support of the warfighter in developing advanced capabilities for defeating many types of enemy targets and platforms, and the recent and ongoing work described within the review of terminal ballistics demonstrated how ARL continues to build upon its tradition of excellence. ARL's efforts in terminal ballistics address both fundamental and urgent Army warfighter needs of great importance. The linkages between the research and technology presented and the ties to Army military vehicles and weapons were clearly demonstrated. The overall quality of ARL's applied research and development is very high. There is, as realized by ARL management, a need to increase focus on the basic research that will underlie future developments. ARL's existing science and technology work in the ballistics area is very well served by the current Aberdeen Proving Grounds infrastructure and facilities. There was clear evidence of speedy response to changing needs to support the warfighter with innovations in ballistic survivability and lethality. ARL's experimental program concerning threats is quite detailed and demonstrates commendable knowledge of the evolving threats. The spectrum of armor design demonstrated a broad array of technical approaches and flexible and rapid response. ARL's staff is clearly motivated and competent, and the staff members articulated a well-defined line of sight from their research to the mission of the Laboratory and to the warfighter.

The overview presentations for the materials for the terminal ballistics area were very impressive and provided a rationale for the diverse materials issues under investigation; the researchers have gained from the recent combat experience and lessons learned from in-theatre observations. The evolving fundamental and applied projects focused on the science of penetration mechanics; the development and implementation of new imaging and velocimetry diagnostics aimed at the quantification of penetration linked to lethality; and a view into the continuum-level models under development for ceramic material

response that attempts to bridge the scale from mesoscale to macroscale. The utilization of advanced diagnostics to quantify the time-dependent penetration behavior of ceramics is both innovative and crucial to the development of models capturing the physics involved in armor penetration and thereby seminally important to design from the perspectives of both survivability and lethality. Innovative mesoscale models from actual material reconstructions are under development to inform macroscale continuum models. Improvements were made in coupling of constitutive models to the host codes to better handle the failure and fracture of materials. The activities presented that address humans in extreme ballistic environments are well organized, the technical strategy is well posed, and the current state of science and technology in this area is well defined. The design, modeling, and testing of the warrior injury assessment manikin to test the effects of extreme acceleration and loading effects associated with underbody vehicle blast is clearly an area unique to Army mission challenges and well connected to warfighter needs. This is an excellent innovative and collaborative effort to collect data required for predicting injuries to support the design of an anthropomorphic test device and sensor placement on it.

The ARL effort examining small combat units and scalable effects through new and effective systems appears well conceived and thoughtfully planned.

Several overarching opportunities and challenges were identified for ARL's enterprise in terminal ballistics, including these:

- Examples of how the Army Research Office's (ARO's) individual projects fit into Army overall goals and relate to one another and to other ARL projects would facilitate the Board's assessment of the quality of ARL's S&T work.
- A rigorous, formal internal validation program is needed for ARL to quantify the extent to which the physics within the broad spectrum of ballistics models is being developed to accurately describe the physics operative. Given the importance of such models to develop predictive design capability in support of current Army programs and future system, platform, and equipment development, increased emphasis on validation is warranted.
- The staff is not visible in professional societies and technical conferences to the level that their accomplishments and scientific expertise warrant. While obviously the sequestration and travel restrictions have negatively affected staff interactions with the outside S&T community, the lack of interactions through conferences and professional associations will have a deleterious effect on collaborative efforts and on maintaining the edge in areas of expertise; it is therefore important to address this as soon as possible.
- It is important to apply increased efforts to ARL's damage and failure modeling across the spectrum of materials of relevance, given its importance to ballistics science and technology. These physically based damage models need to include the statistical aspects of how and where damage evolution and failure occur in a material.

It appears crucial for ARL to develop, for the area of terminal ballistics, its strategic vision behind internal investments, program and mission deliverables, and staff planning to support the needs of the Army of the future. This strategic planning appears particularly poignant as the future ground combat vehicle design pathways are fixed. For example, while glass, effectively confined, is known to have potential for contributing to the defeat of shaped-charged jets, explosive reactive armor (ERA) and even nonexplosive reactive armor (NERA) have greater potential, and ERA is already being utilized with great effectiveness.

HUMAN SCIENCES: SIMULATION AND TRAINING TECHNOLOGY

This assessment is the Board's first in-depth review of the Simulation and Training Technology Center (STTC) since its merger with the ARL's Human Research and Engineering Directorate (HRED) in 2010. Overall, STTC has a clear and substantive mission to enhance military readiness by optimizing behavior and mission performance of individual soldiers and of small units or teams. To accomplish this mission, STTC engineers and scientists perform research, development, and assessment of modeling and simulation-based training technologies to assure cost and pedagogical effectiveness.

The problems being tackled by STTC are large, complex, and important and have huge potential value to Army mission readiness and effectiveness. STTC's efforts are focused in five broad areas: (1) designing, developing, and assessing adaptive and intelligent training technologies; (2) enhancing the state of the art of physics-based synthetic environment modeling; (3) assessing the extent to which training in virtual environments leads to better learning outcomes; (4) developing and testing physical-model- and software-based simulations for diverse training applications such as medical triage, dismounted soldier operations, or training on specific ground platforms; and (5) conducting research and development (R&D) to enable advanced distributed simulation.

STTC is tackling a number of very challenging technical problems in the five areas of training technology that have great potential to set the standards across the Department of Defense (DoD). Technical problems include identifying, for example, how to develop tutoring systems that are adaptive to individual learners, how to best manage instructional experiences, how to make synthetic entities behave more intelligently in training simulations, and how to make training simulations more interoperable. STTC researchers are pushing the state of the art of simulation in the cloud and protocols for advanced distributed simulation (ADS). The ADS group has a unique opportunity to lead future developments across the DoD in these areas. The STTC work is demonstrably significant and valuable in specific application domains (e.g., simulations of battlefield medical situations), as well as the design of general tools for simulation (e.g., the generalized intelligent framework for tutoring [GIFT]) to make it possible for others to rapidly create new training modules for new content areas. Laudable progress has been made to date in the development of GIFT and in the incorporation of this framework within the computer game Virtual Battle Space II, now being used by the Army for training.

STTC has historically been strong in computer science and engineering, and it has developed a number of successful technology-enhanced training products. The Board's assessment recognized these accomplishments and also examined how the performance of the STTC might be improved through the integration of additional scientific expertise, exposure to new or alternative scientific approaches, and tactical consideration and staging of project goals.

The training technologies being developed at STTC have significant implications for humans and their ability to acquire task-critical skills and to become proficient performers. Therefore, the design and development of effective training technologies and systems needs to be an interdisciplinary enterprise necessitating an early and balanced collaboration of computer science and human science inputs. The merger of STTC into ARL in 2010 brought together STTC's core competency in computer science with HRED's core competency in the human sciences, creating huge potential for new productive synergy. The Board's most recent (2011-2012) report observed that the integration of the STTC into HRED creates great opportunities for human factors influence on STTC products and STTC enhancements of traditional HRED endeavors. While some progress toward this goal was evident in the present assessment, the merger of STTC with HRED needs to be accelerated to a higher level, with greater emphasis on and integration of human sciences into the program of work. For the most part, the quality (e.g., experimental design and statistical analysis) and outcome value of the research presented by STTC would significantly benefit from greater engagement of human science expertise (e.g., human factors and the cognitive and social sciences).

The problems being tackled by STTC are complex and very relevant to the broader modeling and simulation community. There are many researchers working on these issues both in academia and in other military laboratories outside the STTC environment. STTC researchers need to clearly define and focus their efforts within the broader scientific community, identifying precisely where they expect to advance the state of the art and how the research is framed by the extant scientific literature.

The Orlando-based leadership and scientific research groups exhibited a high level of professionalism, commitment to high technical standards in their projects, and a broad appreciation of their role in enhancing military and human outcomes. The esprit de corps and desire to integrate innovative and effective research strategies were notable in both research teams and leadership. Investment in professional development and training of junior scientists was integrated as a priority of the program. The STTC is an excellent research unit that embodies high technical standards and a strong operational attitude.

HUMAN SCIENCES: TRANSLATIONAL NEUROSCIENCE

The goal of the translational neuroscience (TN) program is to better understand soldier function and behavior in complex real-world (i.e., operational) settings in order to enhance soldier system performance. The TN group conducts foundational and enabling R&D for development of fieldable technologies that leverage state-of-the-art neuroscience, human factors, psychology, and engineering. The TN program at ARL is a unique and important effort whose objectives, if successfully accomplished, have potential to be a game changer for research on soldier and mission effectiveness. The group has concentrated its efforts on three research thrusts:

1. *Brain–computer interaction (BCI) technologies.* Enable mutually adaptive brain–computer interaction technologies for improving soldier-system performance.
2. *Real-world neuroimaging*. Assess those aspects of brain function that can be usefully monitored outside the laboratory setting and identify and/or develop the technologies that are best adapted for this purpose.
3. *Brain structure function couplings***.** Translate knowledge of differences in individual brain structure and function to understand and predict differences in task performance.

The TN group is tackling key technology bottlenecks to moving neuroscience from the laboratory to the field. For example, they are exploring (1) the integration of other sensing modalities (e.g., electrocardiography [ECG], electromyography [EMG], galvanic skin response [GSR], and eye movements) into electroencephalogram (EEG)-based BCI applications; (2) approaches to overcome real-world limitations for use of the electrode system so that it works with hair, slips on and off easily without significant setup, and has high enough sensitivity to capture the signals necessary for specific tasks; and (3) the development of nonproprietary dry electrodes, which, if successful, could significantly impact medical EEG, human factors, neuroeconomics, and neuromarketing and could lead to important new applications.

From 2009 through 2013, the TN group has made significant gains in publication rates and quality (from 16 publications in 2009 to 44 in 2013, including an increase in publications in peer-reviewed journals from 6 in 2009 to 17 in 2013); numbers of postdoctoral researchers (from 2 in 2009 to 11 in 2013); outreach and mentoring activities (from none in 2009 to 7 in 2013); and level of external funding (from $730,000 in 2009 to $10.75 million in 2013). On these measures, the group has attained a level found at many neuroscience groups at first-tier academic institutions.

As reviewed, the TN portfolio comprises a well-balanced mix of difficult and challenging fundamental science and engineering development problems that are well matched to the core competencies of the science staff and leadership and the emerging needs of the Army mission. The staff has continued to grow, attracting highly motivated early-career scientists from a well-dispersed set of universities, with the resultant benefits of fresh intellectual capital and a productive competition of ideas.

Overall, the quality of the TN research presented, the capabilities of the leadership, the knowledge and abilities of the investigators and their scientific productivity, and proposed future directions are impressive. The work is well aligned with the clear and substantive mission to move neuroscience from the laboratory to real-world military settings (i.e., going from the bench to the battlefield). The TN group conducts high-quality neuroscience research that is routinely validated by its publication in good, peer-reviewed journals and is on a par with work at a good university neuroscience department.

INFORMATION SCIENCES: AUTONOMOUS SYSTEMS

Many of the ARL internal research projects in the autonomous systems enterprise are of very high quality and in general have benefited from engagement with other research institutions, including partners in the Collaborative Technology Alliances (CTAs).[1] For each of the key areas—perception, intelligence and planning, human–robot interaction, and manipulation and mobility—the overall technical quality of the work is high and is being recognized as such through publication in archival journals and proceedings of recognized conferences and symposia. Also, the recent Research@ARL monograph on Autonomous Systems[2] is commendable. For most of the work reviewed, the scientific quality is comparable to that at other federal research laboratories and at national and international universities. The research staff are very well qualified to undertake the research projects and are broadly aware of the state of the art in the field and ongoing research at other institutions. The laboratory facilities and the infrastructure are state of the art and supportive of the ongoing research activities.

Research in the area of manipulation and mobility is closely linked to the ARL's Collaborative Technology Alliances (CTAs) in autonomous systems, where significant collaboration with those partners is to be found. Work related to self-righting robots is of a very high caliber and also has direct applications in the field. The PiezoMEMS research and associated small robotics effort, in the Board's judgment, is first rate, with elements—specifically, the work in motion generation at the MEMS scale—that are seminal.

The research projects in the area of perception are of a high caliber. The focus of the work is on developing techniques that allow for developing a description of the robot's environments from sensor data. While there has been considerable progress toward describing environment for the purpose of mobility, deriving higher-level descriptions such as subtle cues and references that distinguish different behaviors and intents, recognition of specific classes of objects and features that are directly relevant to tactical behaviors, and labeling of object, features, and terrain classes remain a challenge. The primary accomplishments in robotic intelligence are advances in mapping capability, control for communications, and cognition. Much of this work is being published in top journal and conference venues (including the *International Conference on Robotics and Automation*, the *Institute of Electrical and Electronics Engineers Proceedings*, and the *International Journal of Robotics Research*), which attests to the overall quality of the research.

In the area of human–robot interaction (HRI), research at ARL is looking at design issues for safe operation of autonomous reconnaissance systems in complex environments. The experimentation conducted at Fort Benning has yielded an important basis for making design decisions. For example, experiments have demonstrated voice commands to be suitable for discrete actions but less so for controlling continuous processes. Similarly, the research has demonstrated how audio cues in 3D improve situation awareness in telepresence tasks.

While there was considerable variation in both the quality and impact of the research presented, the researchers were largely cognizant of the progress in their fields, and that had a noticeable impact on their own work. ARL has recently recruited a number of very promising early-career scientists. It is important to ensure that they receive appropriate mentorship and career development opportunities as they develop their individual research portfolios. The new indoor Military Operations on Urban Terrain

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[1] There are currently two active CTAs related to autonomous systems: Micro Autonomous Systems and Technology (MAST) and Robotics.

[2] Research@ARL: Autonomous Systems. Available at http://www.arl.army.mil/www/pages/172/docs/Research@ARL_Autonomous_Systems_July_2013.pdf. Accessed September 20, 2013.

(MOUT) facility was impressive and will go a long way in furthering the goals of the intelligence and planning program. The tour of the ARL Sensors and Electron Devices Directorate's Specialty Electronic Materials and Sensors Cleanroom Research facility helped the review team understand the infrastructure support available to ARL researchers.

ARL has a leading program in the area of small-scale robotics. A demonstrated ability to design, fabricate, and test these devices gives it a place of distinction in this field. Similarly, research in the area of perception is being performed at a high level. With a mission to develop machine understanding of objects, actions, and inter-relationships in an environment, this work is critical for advancing the state of autonomous systems. Ongoing research is focused on making advances in unsupervised human detection and in sensing and perception capabilities on constrained platforms. Research in the areas of human–robot interaction and intelligence are addressing important problems of mapping, cognition, and communication, as well as issues related to trust in autonomous systems. This research is cutting-edge, and portions of the work are poised for successful transition to applied research.

All elements of the autonomous systems research program at ARL have continued to show progress, both in the quality of work and dissemination of results in distinctive publications. The program focuses on mobility and manipulation of robotic devices and on technologies that improve the usefulness of these devices such as intelligence, perception, and improved human–robot interaction. The ARL research program is part of a larger collaborative effort involving external partners. A better definition of the role of the internal research in the overall program goals and continued collaboration with partners is strongly encouraged.

It was not clear how the individual research projects in each of the four areas representing the ARL autonomous systems enterprise fit within the larger research effort. Without such a roadmap, there is very little indication of the connectivity of the research projects in either the subareas or across the enterprise.

At a fundamental level, ARL can take additional steps to enhance the quality and impact of its research efforts. There is a trinity in research and development: analysis, computation or simulation, and testing. Analysis is essential, and there is room for improvement on this front, before one proceeds with numerical simulation or building and testing artifacts. Results from analytical modeling can guide the subsequent steps in development and identify possible missteps—this analytical component needs to be integrated into the approach to research.

MATERIALS SCIENCES: BIOMATERIALS, ENERGY MATERIALS AND DEVICES, AND PHOTONIC MATERIALS AND DEVICES

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, according to the ARL. Materials research efforts and expertise are spread throughout the ARL enterprise. As the ensemble of the materials discipline and capabilities, the area of materials science is one of ARL's primary core technical competencies.

All the projects reviewed are engaged in collaborative efforts to various degrees; this is commendable. More excellence can be achieved by working on the efficiency of collaboration to deliver additional focus, quality, and selection of projects. Internal collaboration across the divisions and directorates is as beneficial as extramural collaboration.

In today's fast-moving technological landscape, additional opportunity is presented by the challenge to effectively utilize commercial technologies, particularly in the areas of wearability, mobility, and connectivity, which are critical to the well-being of the soldiers. A systematic, structured effort to scout technologies from the private sector to complement in-house projects will be highly rewarding.

As technology marches on at an unprecedented pace, it will be important that new approaches to shorten the research cycle (from science to useful product) are always on ARL's radar. A concerted effort to understand future needs and to craft projects relevant to the future is the ultimate challenge and opportunity. To this end, the materials genome initiative is one example to track.

Overall, the researchers and the management are of high caliber and deserve kudos. Researchers appeared ebullient and passionate about their work. Most of the projects presented are excellent and are having a pervasive impact. The scientific soundness and the use of the fundamental sciences are outstanding. It is commendable that the ARL materials sciences area comprises a good mix of talents, ranging from experienced, savvy scientists and engineers to bright, early-career professionals. The project portfolio fits well with global thrusts and the national agenda, with research projects falling at the intersection of the pillar technologies of biotechnology, nanotechnology, advanced materials, energy, and the environment.

Some of the projects in the portfolio are particularly impressive. The biomaterials group is making noteworthy progress, following the Board's previous suggestions to recruit a new branch chief and to begin to establish a long-term program in biotechnology. The project on synthetic biomolecular materials offers a high level of Army significance by addressing the needs in situation awareness and force protection in the areas of on-demand production of biomolecular sensing materials in response to new and emerging hazardous threat materials, functional biomolecular materials that are stable in austere environments, persistent surveillance, and ubiquitous sensing. The project has already shown success by developing iterative and integrated multiscale computational biology capabilities—this is top-notch research. The project has also demonstrated for the first time rapid development of peptides as synthetic alternatives to antibody-based bioreceptors, which are difficult to produce and maintain in the field. The use of biogenerated fuel to drive a fuel cell and generate a periodic power boost is another research project important to the Army.

ARL is a technology-driven and warfighter-focused institution: Developing technologies to deliver ubiquitous power and energy for warfighters is a compelling mission. The project on hydrogen production from water by photosystem for use as fuel in energy conversion devices offers promise. The project on nonnoble metal catalysts for alkaline fuel cells studies the catalysts supported on graphene. Impressive power density (300 $mWcm^{-2}$ at 60°C) was demonstrated using a Pt-free cathode with an anode of standard carbon-supported Pt. When the performance can be improved further and stability demonstrated, this could represent a significant breakthrough. For lightweight, quiet, efficient, and reliable power sources for Army applications to enhance soldier combat capability, the project on fuel cells for military applications tests and evaluates commercial technologies, namely, direct methanol fuel cell and solid oxide fuel cell (SOFC) systems. Fuel cells reduce weight and decrease the logistic burden associated with batteries. The 300 W SOFC systems, operated on propane, can be thermally cycled more than 40 times between room temperature and 800°C without significant degradation and can be heated to 800°C in less than 10 minutes. The system was successfully tested in an unmanned aerial vehicle. This represents an upward potential for Army applications.

In the area of photonic materials and devices, the accomplishments of the project on electromagnetic modeling of quantum-well infrared photodetectors (QWIPs) are laudable. The model described explains the quantum efficiency (QE) of all existing detector structures, including the most advanced optical effects, and expresses the detector QE in terms of the material's absorption coefficient and the volumetric integral of vertical electric field. Because affordable, high-speed, high-resolution, long-wavelength infrared (IR) cameras are critically important to the Army's night vision, large area surveillance, and navigation in degraded vision environments, the success of this project is of enormous value. As a leader in QWIP technology, ARL can leverage this achievement to develop advanced technology and to strategically brand its leadership.

Another high-impact project is developing a low-cost, III-V, direct-bandgap long-wavelength infrared (LWIR) detector for night-vision technology. LWIR detection is a niche Army technology requiring dedicated equipment and highly specialized skills and tool sets. The research involves the growth of defect-free unstrained and unrelaxed InAsSb material on binary substrates, such as GaSb, InSb, or InA. This Ga-free InAsSb detector is expected to be a disruptive technology for the LWIR field and to potentially replace the costly II-VI-based technologies.

In laboratory physical facilities, state-of-the-art equipment and instruments are available to perform quality research work, and there is a high level of material characterization capabilities—for example, ultrafast THz, nano-NMR (nuclear magnetic resonance), time-resolved ultraviolet (UV) materials growth and characterization—and a clean room fuel-cell laboratory, all of which are supported by trained and knowledgeable personnel. However, synergistic capabilities can be further harvested through the tie-in of facilities across divisional branches as well as through collaborations with targeted external facilities.

CROSSCUTTING RECOMMENDATIONS

The metrics through which ARL, as a research organization, internally measures and quantifies the quality of its S&T research across the spectrum of its mission space were not provided to the Board. The options could include the number and impact factor of publications or the number of transitions to operational use to the warfighter. Definition of such metrics, and any relevant data, could enhance the impact of the ARLTAB assessments.

The mix of low-risk and high-risk research to achieve an optimal balance continues to be a crosscutting issue for all of ARL's S&T programs. ARL indicated that many of the Director's Strategic Initiative (DSI) projects and 30-50 percent of the Director's Research Initiative (DRI) projects go on to become core efforts.[3] While ARL is working for ways to encourage innovation impacting mission-critical programs, making it safe to fail is a necessary part of encouraging high-risk projects. Internal research investments in successful innovations and high-risk research expectations are in conflict. Risky research is likely to fail most of the time. If success is expected of nearly all projects supported by discretionary funds, staff cannot be expected to propose risky ones. Strategic management discussion of the objectives and expectations for DRI and DSI projects and how these precious funds are aligned or feed longer-term programmatic efforts is encouraged.

ARL's staff visibility in professional technical societies and technical conferences is not to the level their accomplishments and scientific expertise warrant. While it is clear that the sequestration and travel restrictions have negatively affected staff interactions with the outside R&D community, the long-term continuation of restrictions on external technical interactions will be significant. Lack of interactions through conferences and professional associations will negatively impact both collaborative programmatic efforts and maintaining the edge in areas of expertise. This has clearly already affected ARL staff morale, produced opportunity cost, and will pose serious consequences to staff retention and hiring in the future. Moreover, ARL's strategic focus on innovation through adoption and development of scientific ideas and insights from the scientific community cannot be applied to solve Army problems if the focus is forced solely inward. If sustained, a "not-invented-here" syndrome is nearly impossible to avoid in the future, leading to the internal reinvention of wheels that would be better brought in from outside.

Steps to improve the overall ARL research enterprise include the following:

Recommendation 1. ARL should require researchers to clearly articulate the existing technical challenges in their research and how and why proposed tools and methods are likely to resolve those challenges.

Recommendation 2. To allow for setting meaningful goals and adopting a research agenda that targets nonincremental advances, ARL should require all researchers to identify precise metrics against which progress can be gauged.

Recommendation 3. As ARL continues to build its research staff, ARL should give some attention to bringing in mid-career and senior personnel to mentor the outstanding early-career scientists who have been recruited.

Recommendation 4. ARL should look for additional ways to increase interaction of its researchers with leaders in industry and academia, given that limitations on travel have restricted this important function.

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[3] ARL uses the DSI and DRI research projects to build new research capabilities in long-term, high-risk scientific areas with very high potential payoff to the Army mission. DSI projects are typically $500,000 to $1 million per year while DRI projects are $250,000 per year.

Recommendation 5. ARL should focus on developing a mature framework to guide the conception, design, development, and testing of small, unmanned autonomous systems, including definitions of pertinent parameters and their domain (values).

Recommendation 6. ARL should adopt a systems integration approach as a fundamental research thrust.

The details of how ARL is leveraging ARO's 6.1 investment in support of the near-term and long-term Army strategic vision was not always clearly presented to the ARLTAB panels. Examples of how individual ARO projects fit into the Army's overall goals and relate to one another and to other ARL projects would facilitate the Board's tasking to assess the quality of ARL's S&T.

1

Introduction

This introductory chapter describes the biennial assessment process conducted by the National Research Council's (NRC'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:

> An ad hoc committee to be named the Army Research Laboratory Technical Assessment Board (ARLTAB), to be overseen by the Laboratory Assessments Board, will be appointed to continue the function of providing biennial assessments of the scientific and technical quality of the Army Research Laboratory (ARL). These assessments will include findings and recommendations related to the quality of ARL's research, development, and analysis programs. While the primary role of the ARLTAB is to provide peer assessment, it may offer advice on related matters when so requested by the ARL Director. The ARLTAB will provide an interim assessment report at the end of Year 1 of the assessment cycle and a final assessment report biennially and will be overseen by the Laboratory Assessments Board. The ARLTAB will be assisted by five separately appointed panels that will focus on particular portions of the ARL program.

The charge of 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. ARLTAB is charged to review the work in ARL's five core technical competencies (ballistics sciences, human sciences, information sciences, materials sciences, and mechanical sciences) 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 activities of ARO and ARL are coordinated.

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 also may 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 NRC panels, each of which focuses on one of the core technical competencies of the ARL enterprise. The ARLTAB's assessments are commissioned by ARL itself rather than by one of its parent organizations.

For this assessment, the ARLTAB consisted of six leading scientists and engineers whose collective experience spans the major topics within ARL's scope. Five panels, one for each of ARL's core technical competencies, report to the ARLTAB. Five of the ARLTAB members serve as chairs of these panels. The panels range in size from 17 to 32 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. From among the total of 117 panel members, 61 members participated in the reviews that led to this interim report. All panel and ARLTAB members participate without compensation.

The NRC 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 research and development (R&D) laboratories, leading academic researchers, and staff from the Department of Energy national laboratories and federally funded R&D centers. Thirty-six of them are members of the National Academy of Engineering, and seven are members of the National Academy of Sciences. A number have been leaders in relevant professional societies, and several are past members of organizations such as the Army Science Board and the Defense Science Board. ARLTAB and its panels are supported by NRC staff, who interact with ARL on a continuing basis to ensure that ARLTAB and the panels receive the information they need to carry out their assessments. 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 the ARL's activities. Biographical information on the ARLTAB members appears in Appendix B.

The five panels will, during the 2013-2014 period, review the following ARL core technical competencies:

- Panel on Ballistics Science and Engineering: protection, lethality, and survivability/lethality/vulnerability analysis;
- Panel on Human Factors Science: translational neuroscience, soldier simulation and training technology, soldier performance (perceptual sciences and physical–cognitive interaction), and human systems integration;
- Panel on Information Science: autonomous systems, network sciences, atmospheric sciences, and high-performance computing;
- Panel on Materials Science and Engineering: power, energy, photonics, biological sciences, electronic materials and devices, materials in extreme environments, and multiscale modeling; and
- Panel on Mechanical Science and Engineering: propulsion, combustion, mechanics, and diagnostics.

The current interim report summarizes the findings of the ARLTAB from the five reviews conducted by the panels in 2013. The remainder of the core technical competencies will be reviewed in 2014, and the final, biennial report, to be prepared in 2014, will subsume the current interim report and will add findings from the 2014 assessment.

PREPARATION AND ORGANIZATION OF THIS REPORT

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. Most of the information exchange occurs during the annual meetings convened by the respective panels at the appropriate ARL sites. Both at scheduled meetings and in less formal interactions, ARL evinces a very healthy level of information exchange and acceptance of external comments. The assessment panels and ARLTAB engaged in many constructive interactions with ARL staff during their annual site visits in 2013. In addition, useful collegial exchanges took place between panel members and individual ARL investigators outside of scheduled meetings as ARL staff members sought additional 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 is needed because the panels are purposely composed of people who—while experts in the technical fields covered by ARL's core technical competencies that they review—are not engaged in collaborative work with ARL. Technical briefings for the panels focused on the R&D goals, strategies, methodologies, and results of selected projects at the laboratory. Briefings are targeted toward coverage of a representative sample of each core technical competency area over the 2-year assessment cycle. Briefings include poster sessions that allow direct interaction among the panelists and staff of projects that were not covered in the briefings.

Ample time during both overview and 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 2013 ARLTAB meeting refined elements of the assessment process focused on ARL's core technical competencies, including read-ahead materials, review agendas, and expertise required within the panels.

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/or 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 above, 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. *Effectiveness of interaction with the scientific and technical 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;
2. *Formulation of projects' 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;
3. *R&D methodology.* 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; and
4. *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.

APPROACH TAKEN DURING REPORT PREPARATION

This report represents the ARLTAB's consensus findings and recommendations, developed through deliberations that 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 2013. 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 his 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 NRC procedures before being released.

The ARLTAB applied a largely qualitative rather than quantitative approach to the assessment. The approach of 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 the 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 nonexhaustive 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 the ARL work and apparent specific elements of ARL's resource infrastructure that are intended to support the technical work. Collectively, these highlighted examples for each ARL core technical competency area 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.

REPORT CONTENT

This chapter discusses the biennial assessment process used by ARLTAB and its five panels. Chapters 2 through 6 provide detailed assessments of each of the ARL core technical competency areas reviewed in 2013. Chapter 7 presents findings common across multiple competency areas. The appendixes provide the ARL organizational chart and its mapping to the core competency areas reviewed in 2013, biographical information on the ARLTAB members, and the assessment criteria used by ARLTAB and its panels, and a list of acronyms found in the report.

2

Ballistics Sciences: Terminal Ballistics

INTRODUCTION

The Panel on Ballistics Science and Engineering at the Army Research Laboratory conducted its review of ARL's terminal ballistics program, on August 20-22, 2013. This chapter provides an evaluation of that work, recognizing that it represents only a portion of ARL's ballistics sciences core technology competency portfolio.

This year's presentations to the Panel outlined the breadth and scope of ARL's terminal ballistics scientific and engineering research efforts during 2013. These programs span the gap between basic research that improves fundamental understanding of scientific phenomena and technology generation that supports terminal ballistic developments and fielded system upgrades. ARL's terminal ballistics mission scope is principally centered within the Weapons and Materials Research Directorate (WMRD) and the Survivability and Lethality Analysis Directorate (SLAD). These directorates execute their mission of leading the Army's research and technology program and analysis efforts to enhance the protection and lethality of the individual soldier and advanced weapon systems.

ACCOMPLISHMENTS AND ADVANCEMENTS

The Army Research Laboratory has a strong record of achievement and timely support of the warfighter in developing advanced capabilities for defeating many types of enemy targets and platforms over many years, and the recent and ongoing work described in the review of terminal ballistics demonstrated how ARL continues to build on its tradition of excellence in protecting the warfighter. The review was divided into topic areas, including technical keynote presentations and posters covering materials for terminal ballistics, penetration mechanics, humans in extreme ballistic environments, and computational terminal ballistics. The speakers and the presenters of posters demonstrated considerable knowledge of the technical areas addressed, displayed strong enthusiasm for their work, and showed dedication to the missions of ARL, supporting the warfighters and national defense. ARL's efforts in terminal ballistics address both fundamental and urgent Army warfighter needs of great importance. The linkages between the research and technology presented and the ties to Army military vehicles and weapons were clearly demonstrated. Specific accomplishments and advancements in each of the topical areas are summarized below.

Materials for Terminal Ballistics

The overview presentations for the materials for terminal ballistics area were very impressive and provided a rationale for the diverse materials issues under investigation; the researchers have gained from recent combat experience and lessons learned from in-theatre observations. The study of small munitions, specifically striving to build linkages between materials and ballistic performance, was very positively viewed; ARL is encouraged to continue to pursue this direction as a pathway to increased predictive capability. Continued modeling and simulation (M&S) efforts to bridge the boundaries between mesoscale and microscale are encouraged. The organizational effort to encourage students in the science, technology, engineering, and mathematics (STEM) fields and to provide existing personnel with international and university connections is also considered to be very positive.

Many of the materials for ballistics programs reviewed were very impressive. For example, investigation of next-generation aluminum alloy armor and the evolution of the Eglin armor steel are both promising research topics. Aluminum alloy armor design and the materials manufacturing technology of these alloys with superior ballistic performance are key to controlling material and fabrication costs while supporting lighter weight technologies for the Army. Research to develop an available Al alloy with desirable performance but with reduced costs is key to this strategic direction in armor and vehicle design. The use of THERMOCALC, a state-of- the-art thermodynamics modeling program, to modify the Al alloy 2139 composition, particularly reducing the silver content, is very promising. Continuing to partner with industry on alloy development to achieve an Al alloy with similar properties, yield strength, fracture toughness, and formability at a lower cost is clearly the right direction for this research. Altering the alloy chemistry of cast Eglin armor steel with the aim of using this material for underbody blast resistance is a very promising technology to address both increased blast performance and reduced manufacturing and assembly costs. Development of the manufacturing capability for net-shape single-piece underbody manufacturing was very impressive. Simulations of the solidification during casting and, after that, the blast performance using currently available M&S tools, along with experimental testing as an integral part of the development process, were both technologically state of the art and clearly aimed at addressing important Army vehicle needs.

Exploration of the utilization of nanocrystalline alloys for shaped-charge liners appears to be a very promising avenue of research. Nanocrystalline metals offer the possibility of improved properties (strength, ductility) for shaped-charge applications. Fabricating these materials in bulk by means of powder processing is challenging because grain growth occurs even at low temperatures. In this project, the investigators exploit a thermodynamic approach to stabilizing nanocrystalline grains by populating grain boundaries with a solute element that decreases grain boundary free energy. To achieve this goal, the investigators have developed a simple thermodynamic model for grain boundary free energy and applied it, pairwise, across the periodic table. From this pairing of binary alloys, copper-tantalum was chosen as a candidate material. Ductility was better than that of microcrystalline samples. A warhead prototype has been fabricated that may represent one of the largest bulk components ever fabricated with a uniformly nanocrystalline grain structure. Next, the warhead will be tested. This achievement represents a significant advance in the nanostructured materials field and an impressive achievement for ARL.

ARL work involving the multiscale modeling of noncrystalline ceramics and glass is seeking to develop a physics-based multiscale modeling capability to predict the performance and optimize the design of noncrystalline ceramics and glasses not yet synthesized. A specific goal is to develop a fundamental understanding of why certain chemically substituted glasses exhibit enhanced resistance to penetration by shaped- charge jets and other ballistic threats. This research relates very strongly to the glass research effort, which is focused on shaped charge jet/glass interactions; it is possible that at some point certain results from this study could support the glass research activity. Of particular note was the team's ability to leverage work from other institutions, including new results in nanotechnology, applying experimental equipment from geophysics—for example, the diamond anvil cell—and interacting with glass manufacturing research and development (R&D) teams. This team is striving to work across multiple scales, from nano- to mesoscale, and there is significant opportunity in ARL's efforts to integrate the basic science described during the review with the glass research application work and the experimental tools.

Since 2007, ARL has been developing novel fabrication technologies to advance three-dimensional through-thickness reinforcement (3D-TTR) woven fabrics and composites; the goal of the work has been to enhance ceramic composite armor performance by reducing the ballistic damage zone around the impact point. This research is focused on integrated manufacturing and modeling and simulation efforts that, if successful, will result in materials-by-design tools that enable development of lightweight protection systems. This is more likely to be a structures-by-design development than a materials-by-design achievement, but the work can be useful for the development of 3D-TTR hybrid composite armor. This research is forward-looking and promises to achieve practical armor system design using advanced concepts of 3D reinforcement. Achievement of this goal will require ARL to develop its own internal weaving capability to implement the architecture suggested by modeling or to team with industry. It will be important for ARL to strategically determine which of these two courses of action it deems most promising.

ARL has a long history of projects aimed at elucidating the property–performance relationship of armor ceramics and their applicability to armor design and ballistic enhancement. The armor ceramic projects are pursuing both an understanding of damage evolution mechanisms in silicon carbide-new (SiC-N) under dynamic loading and the use of nondestructive testing to quantify microstructure features within the ceramic, in particular the glassy phase along grain boundaries. SiC-N has been shown to fail under dynamic loading via intergranular fracture. This observation, coupled with its superior ballistic behavior compared to other armor ceramics, led the researchers to conclude that the intergranular grain boundary film (IGF) is key to better ballistic performance for boron carbide (B_4C). Linkage of these observations with further utilization of in situ diagnostics seems a promising approach to quantifying the details of how these ceramics operate during ballistic impact. It will be beneficial to link the damage evolution studies with other research where nondestructive testing using impedance spectroscopy has been shown to be able to identify overperforming and underperforming SiC-N. Using scanning probe microscopy, the researchers were able to map the conductivity of grain boundary phases in the ceramic studied. Quantification of the relationships among microstructure, defect type and distribution of nondestructive characterization data, and ballistic behavior in armor ceramic materials is a laudable goal if used to support lot-acceptance testing for ceramic armor components. This nondestructive testing needs to be closely tied with both traditional ballistic testing and postmortem material damage analysis.

Penetration Mechanics

ARL presented an array of evolving fundamental and applied projects focused on the science of penetration mechanics; the development and implementation of new imaging and velocimetry diagnostics aimed at the quantification of penetration linked to lethality; and a view into the continuum-level models under development for ceramic material response that attempts to bridge the scale from meso to macro.

The utilization of advanced diagnostics to quantify the time-dependent penetration behavior of ceramics is both innovative and crucial to the development of models capturing the physics involved in armor penetration and thereby seminally important to design from the perspectives of both survivability and lethality. ARL's team designed a multiple-head flash x-ray system for real in situ observations of projectile penetration into a ceramic armor surrogate. Rate of observation has been enhanced to obtain better imaging resolution. Because absorption scales with sample thickness, the team has also developed a novel photon doppler velocimetry (PDV) technique to track projectile penetration travel into the sample, enabling larger target studies. The x-ray technique was used to determine dwell time during initial penetration and how that can be used to design stacked ceramic armor.

ARL's ceramic material model development work was highlighted in several poster presentations. Innovative mesoscale models from actual material reconstructions are under development to inform macroscale continuum models. Improvements were made in coupling of constitutive models to the host codes to better handle the failure and fracture of materials. In one example, a predictive tool using the Kayenta ceramic model has been developed to predict the response surface associated with material shear deformation as a function of load. Results of limited ballistic tests performed to test the model showed good correlation with model predictions. This modeling effort is of a high standard, as demonstrated by the authors' peer-reviewed journal article. In addition, work involving finite-element modeling (FEM) of tungsten carbide (WC) penetration into silicon carbide (SiC) was well integrated with experiments performed at various rates and with increasing complexity that favorably predicted dwell transition and penetration velocities in the high-rate loading regime. Adaptation of the plasticity model (Kayenta), originally developed for geological materials, to model the mechanical response (tensile failure) of WC reflects innovative modeling through incorporation of the material model development into shock physics finite-element analysis. This work is well connected to material modeling work conducted at Sandia National Laboratories and the University of Utah. It is important to step up efforts to demonstrate how this knowledge and these insights will contribute to the design of armors effective in defeating WC projectiles.

Research into the development of depleted uranium alternative projectiles, including in a segmented-rod form, has been an area of focused research at ARL for over a decade, when it became clear that cleanup of depleted uranium after warfare is both hazardous and costly. There has been little choice politically, therefore, but to investigate means to further enhance the ballistic-impact performance of conventional tungsten heavy alloy (WHA). A significant achievement has been the development of a rigid-body penetrator, in which the strong and tough WHA contains one or more embedded inserts of very hard tungsten carbide/cobalt (WC/Co). Extensive impact testing has demonstrated that the location of each insert in a segmented-rod WHA is critical to achieving optimal ballistic performance at oblique angles of attack. The use of aligned short segments minimizes or eliminates the susceptibility of a long rod to the bending stresses experienced following oblique impact. Excellent progress has been made in this challenging area. In particular, the embedded WC/Co insert appears to be a solution to the oblique-angle impact problem. Building on this achievement, there is the prospect of further improvements in ballistic-impact performance via the use of inserts of multimodal-structured WC/Co and diamond-hard-faced WC/Co. Notwithstanding this progress, there are strategic needs for further development in this area, given the evolving stratagems of the Army surrounding future weapons and vehicles; these needs are addressed later in this chapter.

ARL's successful application of new experimental instruments and diagnostics in new size and time-scale regimes—including optical photography, flash x-ray cineradiography, and new imaging techniques from other institutions such as the national laboratories—to the quantification of in situ penetration into armor is exciting, and ARL is to be congratulated for actively pursuing these diagnostics. Collaboration with the national laboratories has included the application of models and codes and the use of experimental facilities and instrumentation techniques, both of which are very positive; the project using Los Alamos National Laboratory's proton radiography facilities and applying Lawrence Livermore National Laboratory's PDV technique are particularly noteworthy. Both efforts appear to be especially successful. The principal opportunity (and challenge to ARL management) is how to effectively expand and accelerate this work.

The focus of the imaging and velocimetry technique development for impact studies is to identify, enhance, evolve, and develop current state-of-the-art diagnostics to increase information gathered about material state, structure, deformation, kinetics, and dynamics during impact and penetration experiments. Specifically, this work is addressing imaging diagnostics that push toward greater spatial and temporal resolution, laser-based interferometry diagnostics that probe interactions at enhanced temporal resolution, and diagnostics that can identify material state in a multiple-material mixed environment. Techniques being addressed include high-speed flash x-ray cineradiography, proton radiography, x-ray phase contrast imaging, and multicolor flash x-ray computed tomography that has the potential to resolve multiple materials in a reconstructed 3D space that is critical to predictive model development. This effort can be expected to enhance ARL capabilities important to advancing fundamental understanding of impact/penetration phenomena and is strongly encouraged.

Research investigating phase field modeling (PFM) of fracture and twinning in brittle solids addresses an area relevant to the fracture of ceramic armor materials. This is good and interesting fundamental materials work. The driving focus behind this research is motivated by the observation that polycrystalline armor materials such as ceramics and metals often demonstrate twinning and transgranular fracture at the single crystal scale. In very high strain rate situations, even brittle materials can undergo plastic deformation, by dislocation motion and by deformation twinning, as well as fracture. In order to investigate the competition between twinning and fracture, a PFM has been developed and tested on single-twin and single-fracture events.

For twinning, the free-energy functional includes the elastic field (which changes nontrivially upon twinning) competing with a twin/matrix interfacial free energy. For a single twin forming under an indenter, this model captures both reversible and irreversible twinning. For fracture, the free-energy functional involves a balance between the elastic energy released and the surface formation energy—that is, a Griffith criterion for fracture. Crack initiation and opening were demonstrated in various notched sample configurations. This research is a new application of PFM and offers a promising method for probing shock behavior in complex microstructures. Although the ultimate payoff may be several years in the future, it is an effort worth pursuing. This fundamental research project is building a foundation for future modeling and is considered promising. PFM is a good addition to ARL's suite of computational capabilities.

Composite model development to support ballistics predictive capability is being pursued via numerical models aimed at understanding how the woven portion of the armor package can be optimized to increase penetration resistance. This research specifically addresses implementation of a woven fabric model to simulate the response of soft armor to the impact of a debris cloud generated by buried charge, such as that from an improvised explosive device (IED). Improvements being made to the material model based on experimental work by ARL and academic partners, introducing stochastic variation in the fibers and reductions in stiffness and strength due to the weaving process, are considered innovative and worthy of continued investment. Work is needed to effectively apply the experimental results to further model refinement and to verify the validity and value of the model.

Determination of the mechanisms controlling penetration in lightweight materials is key to achieving future lightweight armors for both personnel and vehicle protection. Results presented for aluminum alloy 1100-O showed that for a 30 percent cold-rolling reduction, a dislocation cell structure was observed; for 70 percent reduction, the cell density increased and a laminar microstructure began to emerge; and for 80 percent reduction, a fully developed laminar structure was formed. This correlation enabled the variation of spallation pullback velocity with shock resistance, with peak shock stress to be investigated for each Al-alloy microstructure. For the 30 percent reduction, the variation with shock stress was not monotonic, whereas for the microstructures with higher dislocation content, the variation in shock resistance increased or at least did not decrease with increasing shock stress. This work provides a possible window into the effect of microstructure on blast resistance. The interaction with university and international research partners was a strong point. The project demonstrates a solid step toward developing an understanding of the effects of microstructure on Al-alloy armor blast resistance using modeling and simulation (M&S) tools. The work reflects good leveraging of interactions outside ARL.

Humans in Extreme Ballistic Environments

The humans in extreme ballistic environments activities appear to be well organized, the technical strategy is well posed, and the current state of science and technology in this area is well defined. The design, modeling, and testing of the warrior injury assessment manikin to test the effects of extreme acceleration and loading effects associated with underbody vehicle blast is clearly an area unique to Army mission challenges and well connected to warfighter needs. This innovative and collaborative effort to collect data required for predicting injuries to support the design and sensor placement on anthropomorphic test devices is to be commended. Ties to the medical communities to map current wartime injuries and subsequently inform vehicle and warfighter equipment to reduce injuries and enhance survivability are excellent. ARL is to be commended on the excellent partnering with university and external experts related to how experiments are conducted and data collected. The program appears to be well run and technically sound, but there appears to be insufficient collaborative activity on the physiological effects of kinetics to inform research on what kinetics can be tolerated—for example, the limits for traumatic brain injury (TBI).

The project on evaluation of the effects of blast and ballistic protection on soldier performance included modifications to two soldier equipment items that positively improved warfighter protection. These items included a helmet support device (to address the tendency of the head to drop forward under the burden of the helmet and night vision goggles) to maintain the helmet in an optimized position for protection and a mandible guard addition to the helmet. The team demonstrated that the mandible guard interferes with common weapon aiming and firing and thus presents an integration challenge. These investigations included both live soldier tests and laboratory assessments. The live soldier tests were performed on a soldier sitting in a chair and a soldier navigating an Army obstacle course. Both projects represent innovative and timely attention to addressing warfighter needs and are examples of excellent integrated research and technology applied to short-term warfighter needs.

The project on soft protection/continuous fiber woven composites is addressing a critical near-term warfighter need for groin protection that balances protection, comfort, and flexibility. Systematic investigation of various available aramid yarns (yarn denier), knits, and felt constructs starting with insights gleamed from the U.K. underwear options already deployed are under evaluation for groin ballistic protection. The scientific and engineering approach addressing this near-term warfighter need encompasses very promising options, and exploration of additional fabrics and weave options is encouraged. Teaming with industry appears particularly crucial to this endeavor.

Two projects, one theoretical and one experimental, are addressing head protection through strongly coupled modeling. The integrated approach for improving low-velocity-impact head protection via an ARL-developed finite-element model (FEM) for head impacts while wearing a helmet is clearly responsive to a key Army priority; such low-velocity impacts may be a result of falling or of exposure to an explosive event. Present helmet pads are effective for impacts at about 10 fps, but the objective of the ongoing work is to increase impact energy absorption from <<10 fps up to tens of fps to 150 *g*. To date, the model has been validated with experimental results in the range 10-14 fps, with interest in extending the validation for <1 to 20 fps. The modeling results presented have indicated pad characteristics that may meet goals, primarily for frangible or frangible elastic materials. Alternatively, an external helmet load-bearing fixture has been conceived. Both novel concepts have been prototyped, and there has been some initial testing. Such out-of-the-box thinking is to be lauded, but it is also reasonable to question whether a helmet is ultimately the correct approach or whether some form of back- or shoulder-mounted head protection device would perhaps be a more effective solution. This project appears to be an excellent example in which the numerical model supports experimental concepts and corresponding experiments verify the model and concept. What makes it a special case is that this work informed out-of-the-box conceptual thinking about external supports for the helmet and even a replacement of the helmet with shoulder- or back-supported head protection. ARL is encouraged to continue pursuing this area of science and engineering.

The work on modeling of the head/helmet system subjected to blast and ballistic loads is leading to the development of a computational framework to define loading response to the head and the interaction with helmets as input to neuro-network analysis. Improvement and further development of the computational effort for both the helmet and the coupling to the head is encouraged. This is in line with the view of the ARL team, which recognizes the limitation of the current model and the importance of exploring new ideas for improvement and linking them to the *g*-force-loading helmet design project.

The use of a torsional Kolsky bar to evaluate high-strain-rate characteristics and quantify the mechanical properties of viscoelastic polymers at very high strain rates has been reported in the scientific literature. This project is in support of quantification of the high-rate mechanical response of human tissues to facilitate the development of constitutive models to describe such tissue subjected to extreme loading. Such polymers could be used as synthetic surrogates for biological tissues and are therefore of interest to experimental and modeling efforts looking at ballistic and blast effects on the body. The experimental measuring techniques are complex, and the Army is on target in attempting to develop this capability. Unfortunately the Army investigators could not replicate the analysis reported in the literature. The finding, if true, is disappointing and important, because mechanical characterization methods at these strain rates are difficult and few. While it is understandable that alternatives are not readily available, it seems that a more rigorous follow-up is warranted. The Army is one of a very few organizations with a mission need for such data. Without more analysis of the Army modeling efforts and plans, one cannot discern the absolute necessity for such data nor the degree of accuracy required, but it seems certain that competence in this area is vital for the military. ARL is encouraged to continue to explore both experimental techniques/diagnostics and constitutive model development in the area of tissue mechanical behavior.

A finite-element approach was developed to numerically model the forces of a bottom explosion on the warfighter's foot and leg below the knee. The resolution of the computational elements supported modeling of all the bones and the soft tissue. Existing data were consistent with the model, so that both the model and data have been shown to yield a result indicating minimal foot damage for a short impulse of low-amplitude and low acceleration but major damage for a much larger amplitude impulse over a longer loading time. The team expects to refine the model and further compare it with experimental data; however, it is nearing sufficient validity to support examination of floor protection concepts that could reduce the impact from under-vehicle blast loading on the soldier. Work to explore extension of the model to evaluate blast effects on the upper leg and torso and potential means for mitigating those effects seems promising. This project presents an excellent example of a combined theoretical and experimental approach to developing a basis for relatively timely and inexpensive engineering trade-offs of concepts to improve vehicle design and safety systems.

The project on methodology for evaluating small-caliber systems involves the application of a previously developed modeling tool to a newer small-caliber weapon. The predictions of the work are comparable to experimental results to the degree necessary for the field. The speed and ease with which this work was completed is ample evidence of the utility of the model for addressing practical military ballistic and warfighter weapon needs. It is, however, difficult to see a clearly defined research component in the current work. Any innovative steps in the construction of the model are years in the past and were not presented. This does not detract from the accomplishments or the successes of this project, but it is not clear what further fundamental development of the model is planned or needed.

The project applying survivability analysis to body armor decisions using the operational-requirements-based casualty assessment (ORCA) code analyzed the torso for vulnerability to frontal ballistic trauma. The analysis was repeated for two body armor configurations. This analysis provided data that could be used to compare the protective benefits of the larger armor against the drawbacks of weight and bulk. A similar analysis was used to compare injury and disability with and without protective undergarments. These data help bolster the case for these safety devices needed to protect the soldier in the field. It will be important to apply the ORCA code to all the classes of warfighter protective equipment deployed in theatre as well as to new equipment being designed and tested, and to clearly link the applications to the effort at validating the ORCA code.

Computational Terminal Ballistics

The lethal mechanisms and the blast and ballistic protection projects provided an interesting and reasonably comprehensive review of the broad scope of ARL work in these areas. ARL has a strong record of achievement over many years in developing advanced capabilities for defeating many types of enemy targets, and the recent and ongoing work described is building upon its tradition of excellence. The ARL effort to examine small combat units and scalable effects that extend through new and effective systems appears particularly well-conceived and thoughtfully planned.

The glass research presentation described in depth work being conducted to develop an advanced fundamental understanding of the fracture behavior of glasses during penetration by a shaped charge jet and details of the interactions between the jet and the fragmenting glass. The effectiveness of glass, whether self-confined or mechanically confined by other materials, to resist penetration by shaped-charge jets has long been known and generally attributed to a dilatancy (bulking) effect, but the excellent experimental and computational work described builds on prior knowledge, particularly work conducted at ARL more than 20 years ago. This project involves a research strategy using highly resolved experimental investigations and high-fidelity computational modeling. The project incorporates state-of-the-art constitutive mechanical models developed at ARL aimed at discovering a mechanism for disruption of shaped-charged jets in glass targets. As such it is establishing a suite of experimental and computational tools that may be potentially applicable to a variety of extended studies. This is outstanding work exemplifying how experimental study and modeling can effectively use discovery science and research to drive innovation. This research is comparable in technical quality to that of other leading laboratories.

The computational terminal ballistics overview described exciting new work focused on the effects of electromagnetic (EM) fields on the formation and breakup of shaped-charge jets. The phenomenon, initially discovered through computational analyses and subsequently examined computationally in some detail as well, will be better understood through systematic investigation in a series of well-structured experiments. The presentation had two major components: a broad overview of computational ballistics and specific results for computational model employment and development for EM armor applications. ARL has enhanced the ALEGRA multiphysics code from Sandia National Laboratories to incorporate ceramics modeling (Kayenta), extended FEM, Lagrangian material tracking, coupled optimization software (Dakota), and magnetohydrodynamics robustness and new materials.

In the computational modeling effort for EM armor, specific accomplishments included successfully applying the enhanced ALEGRA model to assess the behavior of EM armor, identifying correspondence and important differences with experimental results, and developing a prototype design for a compact power source. This project exemplifies how ARL is utilizing and extending the best National Nuclear Security Administration modeling tools to address Army mission projects and deliverables. Coupling of these predictive tools with the combat vehicle vulnerability analysis modeling appears to be an area where a game-changing predictive modeling tool suite could be developed; it could positively impact phenomenological and operational system implementation and performance modeling of the future ground combat vehicle (GCV).

The EM "squish" phenomenon was newly recognized as having potential value in helping to make an advanced capability more effective. The basic physical mechanism is understood, and the Sandia model is used to explore alternative configurations aimed at optimizing the effect. This is the same model, however, used for the jet-induced plasma investigation, which is known to have a discrepancy that may also be relevant to this effect. One expects that the requisite modification of the model mentioned for the jet-induced plasma will also be required to achieve significant further progress in exploring the squish phenomenon.

The project on flow strength of polymers modeling focuses on atomistic to FEM and is an excellent start toward interfacing atomistic and continuum models of polymer mechanical behavior. Expansion of this modeling multi-length-scale approach is strongly encouraged as a path forward to address the distinctive behavioral differences at high strain rates exhibited by polymeric materials.

The modeling and simulation of military operations on urban terrain (MOUT) target penetration project has completed some target analysis and quantified the margin of error. In order to match experimental data, researchers had to divide the solution space and solve the equations using two different techniques. That they were able to predict results within 10 percent is considered to be a strong and very promising technical ARL accomplishment.

The project on reduced-order modeling of underbody blast is an in-house effort that developed a simplified modeling approach amenable to rapid determination of blast-loading histories on critical Army targets. Simplified assumptions are made that attempt to represent the essential aspects of impulse loading without resorting to a detailed three-dimensional (3D) computation of the blast response. This modeling is useful for rapid turnaround system evaluations. Linkage of this modeling to a testing program that evaluates the effectiveness of the modeling is clearly necessary to validate the accuracy and to quantify the margin and uncertainty of the model. The project has also determined a set of analytical solutions that could be used for verification of the simplified numerical model and its mathematical implementation. This work represents a step beyond pure empirical modeling that may be appropriate for

Monte Carlo or system analysis. The simplifications that are used impose a degree of uncertainty in defining loading histories, however, because impulse is an integrated quantity and the uncertainties may be acceptable for some system evaluations. Key to this effort is determining the limits of the applicability of the simplified model approach.

The jet-induced plasma characterization project clearly represents a discovery science project. It is based on a particular concept that guides the parameters of interest. It includes an experimental investigation to characterize the plasma. A Sandia model was employed by Sandia collaborators to capture the characterization in a model of the plasma jet. This comparison and modeling and experiment resulted in the discovery of an apparent discrepancy. Further experimental measurements have begun to determine the source of the apparent discrepancy. As more data are obtained, Sandia plans to revise the computer code and expects that modification to require significant effort. In the meantime, the experimental results have provided evidence that can advance the concept. While much remains to be done to complete the investigation, the next step would be to explore a practical implementation approach to armor protection.

Demonstration of the utilization of reduced-order modeling of underbody blast for estimating and evaluating lower limb soldier injuries in vehicles subjected to blast loading is both important and timely to inform new vehicle design considerations. The project illustrated completed-scale impulse tests of flat plates and V-hulls to validate underbody models, which were used to support analyses of alternatives for joint light tactical vehicles and to inform design strategies for the GCV. Reduced-fidelity models to support system engineering trades and program planning and execution decisions are an extremely important line of model development.

The project on novel penetrator efficiencies is focused on segmented penetrators. It also involves the development of extending rod penetrators. Segmented penetrators were the topic of intensive study at least 20 years ago, but the largely proof-of-concept effort was of limited success. One of the challenges is defining appropriate and credible baselines for comparison, which are greatly needed. The researchers on this current updated look at segmented penetrators appear to understand the importance of developing credible baselines for comparison. Some results to date with respect to achieving and maintaining desired separation in flight and segment colinearity during penetration are promising. The potential benefits of segmented rods may become increasingly evident as impact velocities extend well beyond the current conventional ordnance velocity regime of ≤1,600 m/s. A particularly interesting means for extending the rod close to the target and locking the segments together has recently been transitioned to the U.S. Army Armament Research, Development and Engineering Center (ARDEC) for possible application in next-generation kinetic energy (KE) and depleted uranium (DU) replacement programs. As noted for segmented penetrators, it is imperative that credible baselines be established for performance comparisons to monolithic, nonextending rods.

In the vehicle protection armor modeling project, the goal is to explore armor concepts using modeling and simulation to gain a fundamental understanding of the mechanisms at work and how ARL can exploit them to defeat current and future threats to Army platforms. Proven modeling and simulation tools can be extremely useful in exploring advanced armor concepts. Such tools have been in a continual state of evolution for many years, with much of the work being conducted at the Department of Energy national laboratories. The overall validity with respect to both large-scale deformations and specific material behaviors, as well as the ability of the models to effectively model target/threat interactions for a range of threat types (KE, shaped charges, explosively formed penetrators [EFP], and blast), is critical. This is important work and clearly will be helpful in guiding ARL armor concept development efforts and setting the stage for follow-on, well-defined, proof-of-concept experiments and subsequent advances. Establishing and maintaining a strong link between this modeling work and system testing as validation is key to the development of effective predictive design capabilities. Implementing existing multiphysics modeling capabilities to simulate explosive armor performance, exploring several design possibilities, and conducting appropriate comparative experiments as a basis for modifying the model parameters represent a promising start to the development of a tool for designing explosive reactive armor.

Development of modeling tools for both metallic armor and 3D hybrid composite protection systems appears to be an outstanding contribution to practical armor system design using advanced strength and damage models for metallics and ceramics and concepts of 3D composite reinforcement. The metallic modeling provides computationally based guidance for alloy development for armor applications. Combining strength and damage models followed by a parameter sensitivity analysis to determine which material parameters are most important for reducing penetrator damage in an aluminum (Al) and a magnesium (Mg) alloy represents a strong systematic approach to providing insight into armor design and performance. This analysis demonstrated that the work-hardening parameters characteristic of these materials are most important for new materials design, with failure strain ranked as next in importance. To implement the architecture suggested by 3D composite modeling, it will be important to strategically address the development of weaving capability within ARL.

OPPORTUNITIES AND CHALLENGES

An important overarching consideration in assessing specific research activities ongoing at ARL is whether the work can reasonably be expected to solve short-term critical warfighter needs encountered in theatre or is focused on the long term to have some potential to make a significant contribution to the eventual development of advanced capabilities important to meeting the operational Army's warfighting, peacekeeping, and perhaps other mission needs. If these goals cannot be met, attention can be redirected to other areas.

The opportunities and challenges are presented here in two categories: (1) overarching topics related to ARL's overall science and technology (S&T) enterprise in terminal ballistics and (2) specific succinct opportunities and challenges tied to particular terminal ballistics thrust topics or projects.

Overarching ARL Topics

The materials presented did not always provide details of the programmatic ties and interplay with the ARL integration into the 6.1 (basic research) to 6.7 (operational system development) S&T infrastructures. These details would provide a richer context in which to assess the potential ability of the research to meet current Army needs and support the Army of the future. Further, how ARL is leveraging the Army Research Office's (ARO's) investment to support the near-term and long-term Army strategic vision was not always clear across all the projects presented. Examples of how individual projects fit into Army overall goals and relate to one another and to other ARL projects would facilitate the ARLTAB assessment of the quality of ARL's S&T work.

Model validation, which requires concurrent research of materials properties and performance, was clearly insufficiently defined and elucidated during the review for the majority of the projects presented. Some excellent examples of validation were shown at some level, such as in the MOUT project, but this was not seen throughout the review. Too often, just a computer-based visualization of a model was presented with little or no quantitative comparisons to data. Details of complex material and structural models matter, but these, along with the basis for choosing model parameter values, were seldom discussed. When considerable simplification of geometry or assumptions of material behavior is made, it is important to provide data justifying such approximations. The success of a model in reproducing a visual image of the overall phenomenology is not validation. It is important to achieve delineation on a project by project basis. Is validation sought for that project's scope of work to determine whether a detailed comparison with quantitative data is warranted, or is validation for this project deemed to be the ability to predict trends in response or performance so as to map out regions that would define and limit experiments? A rigorous formal internal validation program is needed within ARL to quantify the extent to which the physics within the broad spectrum of ballistics models is being developed to accurately describe the physics operative. Given the importance of such models to develop predictive design capability in support of current Army programs and future system, platform, and equipment development, increased emphasis on validation is warranted. In addition to the need for an ARL-wide strategic approach to model validation, methods are needed to quantify the margin of uncertainty (QMU) for these models. For example, it is not clear how the ORCA and MUVES-S2[1] models are validated. The reviews often lack sufficient details on how ARL's models are formulated and validated; the sensitivity, if known, to key parameters and variables; and the statistical variations to be expected. Also, it is necessary to present the error bars in comparisons between models and data.

ARL's staff is not as visible in professional technical societies and technical conferences to the extent that their accomplishments and scientific expertise warrant. Obviously the sequestration and travel restrictions have negatively affected staff interactions with the outside R&D community. Lack of interactions through conferences and professional associations will have a deleterious effect on collaborative efforts and on maintaining the edge in areas of expertise. This has already affected morale and opportunity cost, and it will pose serious consequences for retaining and hiring staff in the future. In the poster presentations, there were examples of technical work that suffers from a lack of external collaboration. Moreover, ARL's strategic focus on innovation through adoption and development of scientific ideas and insights from the scientific community cannot be applied to solve Army problems if it is forced inward. If this situation is sustained, a not-invented-here syndrome will be nearly impossible to avoid, leading to internal reinvention of wheels that would be better brought in from outside.

ARL's damage and failure modeling across the spectrum of materials of relevance is less technically evolved and therefore less predictive than the strength and equation-of-state modeling capabilities within ARL presented during the review. It is important to increase efforts in this area, given its importance to ballistics science and technology. Physically based damage modeling needs to include the statistical aspects of how and where damage evolution and failure occur in a material. This includes identification and modeling of the damage and failure mechanisms in biological and soft materials that as a newer field represent a challenging scientific problem. It is also important to explore strengthening the staffing and collaboration in this area with external university and national research laboratories and the medical community.

Materials for Terminal Ballistics

It appears crucial for ARL to develop strategic thinking behind internal investments, program and mission deliverables, and staffing planning to support the ability of the Army to meet the national security mission needs of the future. This strategic planning appears particularly poignant as the future GCV design pathways are fixed. For example, while glass, effectively confined, is known to have potential for contributing to the defeat of shaped-charged jets, explosive reactive armor (ERA) and even nonexplosive reactive armor (NERA) have greater potential, and ERA is already being utilized with great effectiveness. Ceramics similarly can be very effective, but only when very effectively confined, which currently makes them too expensive for implementation in vehicle protection applications. The key questions are therefore these: Which of ARL's current areas of S&T are sufficiently mature in the area of materials for terminal ballistics to meet current and projected performance criteria in specific applications? Which have been found, for reasons of performance or cost, not to warrant further continued effort at the expense of new innovative S&T areas? Better characterizing and qualifying the materials ARL receives from various suppliers will help to make engineered systems deliver the expected performance.

It is important to identify the microstructural features to measure and the property or properties in next-generation aluminum alloy armor that correlate with ballistic performance. It may be strength and (quasi-static) fracture toughness as measured so far, but that remains to be verified. Assessing the ballistic performance of the developed alloy is crucial to determining whether research on this alloy should continue.

[1] MUVES-S2 (Modular UNIX-based Vulnerability Estimation Suite) is a software-based modeling tool.

Mechanical performance of nanocrystalline alloys for shaped-charge liners will certainly be a function of microstructure, which in turn arises from processing. The research would benefit from a grain scale modeling component, including both microstructural evolution (sintering and grain growth) and mechanical response (ductility). When combined, these models can not only predict resulting structures but can also suggest optimized microstructures. This may be a much more efficient approach than iteratively reprocessing to achieve optimized material properties. The Office of Naval Research (ONR) has some interest in these systems. The possibility of partnering with the Navy on this topic is worth investigating. It is worthwhile to expand the research to include variations in the volume fractions of the constituent phases. Near 50:50 compositions are likely to develop bicontinuous nanostructured composites, in which the constituent nanophases are interpenetrating in three dimensions. Such composite structures are extraordinarily resistant to grain coarsening at high temperatures, thus opening an opportunity for high-strain-rate superplastic formation, as observed for a tri-continuous oxide ceramic.

The 3D through-thickness reinforcement (TTR)-hybrid composite armor development effort appears to be a structures-by-design development project rather than a materials-by-design achievement, although this research is viewed as having merit. Since this effort has been under way for more than 5 years, however, it is reasonable to ask what significant achievements it has recorded to date. Has clear proof-of-concept been established? This armor system has a very complex structure and geometry that will be extremely time-consuming to model at the level of the fiber or even the yarn. Considerable simplification will be required, and each level of simplification will require validation by some carefully designed experiments. This level of validation has not yet been done and has not even been planned. Without this, the utility of modeling for further refinement of such woven composite systems is compromised.

All composite armor studies utilize existing fiber chemistries and processes, unchanged by the fiber industry for the past several decades. Translating the 3D-TTR effort from structure-by-design to materials-by-design will require the incorporation of fiber chemistry and processing expertise, either developed in-house or accessed externally. Recognizing the paucity of new fiber development by fiber manufacturers, next- generation materials will likely need to be developed in-house at ARL.

The deliverables to be gleaned from elucidating the property-performance relationship of armor ceramics were insufficiently defined to show what the prior program accomplished. What results have been obtained that suggest this program will provide results useful to the Army? While one possible use could be to support lot-acceptance testing for ceramic armor components, it seems unlikely that it could replace traditional ballistic testing for this purpose. Ballistic testing remains a key acceptance/rejection basis for ceramic-enhanced small arms protective inserts (ESAPI) plates used in body armor. The strategic direction of this project needs to be evaluated.

The project on ceramic microstructures for enhanced ballistic protection appeared to be retreading old ground. The work has shown that ceramics with fine grain size and IGFs have better ballistic performances than those with coarser grain sizes and limited or no IGFs. This work would be significantly enhanced by the use of transmission electron microscopy (TEM) to characterize grain boundary structure and chemistries, because the IGFs are believed to be key to intergranular fracture. Grain size and IFG effects on fracture have been extensively studied, and the researchers need to integrate the knowledge amassed in this extensive literature into their analysis. This program covers a large array of materials ranging from commercial aluminas (why these aluminas were chosen was not clear) to B_6O, AlB_{12}, $AlMgB_{14,}$ and composites. At present there is little fundamental perspective. What is new and promising about this work? Are ARL researchers aware of previous work reported in the open literature or in government reports that has been done assessing microstructure vs. ballistic performance correlations?

The goal of the project on advanced materials and processing for soldier protection is to identify the high-rate mechanisms, materials, and architectures and the innovative processes and concepts for enabling quantifiable improvement in key aspects of soldier-borne protection for both head and body. The focus on improved composite designs for helmets, which is exploring the effects of existing, commercial polymer yarn constructs for better ballistic protection while using state-of-the-art modeling to identify improved yarn ply orientation patterns, is very positive and forward thinking. While integration of this modeling with other types of body armor or lightweight vehicle armor was not discussed, it needs to be strongly encouraged even if the current goal of defeating of a 7.62-mm small arms threat represents a perhaps insurmountable objective in a helmet of a tolerable weight. In the advanced materials and processing for soldier protection project, the focus was on a ballistic helmet capable of defeating theater-relevant small arms threats, new insight and approaches to mitigating the shock and adverse impulses associated with impact, and an ESAPI system solution capable of meeting the objective threats at a 10 percent lighter areal density. The goal of achieving a ballistic helmet capable of defeating 7.62-mm small arms threats, which is very likely only achievable at a total helmet weight that is intolerable to a user, poses a virtually insurmountable challenge. A 10 percent reduction in areal density (AD) for ESAPI body armor is a realistic goal, but the strategic planning needed to achieve this goal was not described. One stated planned accomplishment was initial multiscale technology integration to demonstrate small arms protection at effective AD of 3 lb/ft^2. This is almost certainly not going to happen. The Defense Advanced Research Projects Agency (DARPA) spent many millions of dollars trying to do this for body armor (3.5 lb/ft^2 goal) a decade or so ago and accomplished virtually nothing. The objectives of this project need to be evaluated.

Penetration Mechanics

ARL's penetration mechanics program is an ambitious effort aimed at merging state-of-the-art modeling with new experimental diagnostics. This is a great challenge that could advance the science of penetration mechanics. Predictive capability, however, will only be achieved if bridging the scales from a modeling perspective is strongly pursued, coupled with a strong program in material damage evolution and failure modeling.

The time-dependent penetration behavior of ceramics project described application of a flash x-ray and PDV to reverse ballistic testing of metallic penetrators into subscale ceramic targets; this effort represents a positive application of evolving diagnostics to Army problems. PDV appears to be a useful new tool for large-sample studies able to track particle velocities over longer time intervals than velocity interferometer system for any reflector. This body of work provides real-time data that are critically needed for model development and, thereafter, verification and validation. Although the x-ray technique has been used for years, its use in materials studies remains critical. The PDV work appears to be a key new tool in future ballistic testing, but only if tied to quantitative analysis of the deformation and fracture mechanisms during terminal ballistic experiments and then as input to improving computational models applicable to lethality and protection technologies. Dwell was first recognized as a notable consideration in the performance of hard-faced armors at Lawrence Livermore National Laboratory (LLNL) in the late 1960s. ARL initiated work focused on dwell many years ago. A critical question is: What has dwell-centric research to date achieved toward the development of superior ceramic armor materials? It is necessary that a strategic overview of this topic be undertaken.

Ceramic material model development is an activity of critical importance at ARL if it can lead to creation of a predictive modeling capability for application of ceramics and other materials in Army armor and lethality systems. Significant efforts have been conducted by a number of organizations over many years, including focused work supported by DARPA, that have not achieved the goal stated for the modest ARL effort. ARL claims that improvements have been made in the coupling of constitutive models to the host codes in order to better handle the failure and fracture of materials. What advances with respect to predictive capability have been achieved? ARL also claims that a variety of simplified ballistic experiments that examine the time-dependent failure of materials have been conducted to validate the improved material models and codes. What have these experiments shown? No details that would elucidate these questions were presented.

Research in depleted uranium alternative projectiles is a project crying out for strategic planning and context definition for future Army needs and ties to Army strategic planning linked to new vehicle designs. The presenter stated that significant progress continues in developing nanocrystalline tungsten (W)-based composites as depleted uranium (DU) substitute materials; however, few specific accomplishments were cited. Research to develop non-DU projectile materials having at least comparable performance has been under way for more than three decades. Other ARL work included in the DU-replacement effort that is directed toward improving the performance of (sheathed) tungsten carbide (WC)-based projectiles against oblique targets may be of some value. The researchers need to consider the applicability of diamond-hard-faced tungsten carbide/cobalt (WC/Co) alloys as inserts in segmented WHAs. These materials have been under continuous development for decades, and today they are the materials of choice for drill bits in the oil- and gas-exploration industries. They are available commercially in disc-shaped forms for drag bits and as profiled inserts for roller-cone bits. The diamond hard-facing is actually bonded with Co, as is the underlying compositionally graded WC/Co, thus imparting fracture toughness (bend strength) to the graded composite material. Another option is a multimodal-structured WC/Co, which can be fabricated via liquid-phase sintering of mixed powder compacts, even though the Co content is <2.0 wt-percent; normally, at least 10 wt-percent Co is required to ensure complete densification, which incurs a weight penalty. A denser WC/Co insert that is harder and tougher should be advantageous.

For kinetic energy (KE) penetrator applications, presenters did not explain what they have gained by recently focusing on nanocrysalline materials. The researchers noted that the engineering properties of these new materials remain quite poor. They exhibit minimal ductility and toughness and resist efforts to integrate them into KE projectiles. It may be that this challenge cannot be surmounted. Work with sheathed penetrators was also mentioned. This area was also explored extensively at least as far back as the early 1980s. The presenters did not demonstrate much awareness of prior work in this research area or of lessons learned contributing to the present effort. It is time for some focused strategic thinking on the objectives, the Army needs, and specific goals in this research area rather than continual repetition of past approaches.

Phase field modeling (PFM) of fracture and twinning in brittle solids is tied to the observations that polycrystalline armor materials such as ceramics and metals often demonstrate twinning and transgranular fracture at the single crystal scale. In this work, phase field theory and numerical simulation are used to model these phenomena; this may provide a payoff for the Army in the long run. This project would benefit from interaction with ab initio or empirical atomistic modeling as well as experimental work; it could supply data for input (surface energies, for example) as well as information for validation (twin size, nucleation mechanisms). This work would benefit from integration with the academic phase field modeling community. Collaboration and insights into the state of-the art currently available in this area are yet another casualty of the ill-advised government policy that restricts conference travel. In PFM, interfaces are diffuse, which may affect fracture propagation (by smearing the crack tip discontinuity). The effect of the diffuse interface on fracture predictions merits attention. The extent to which this work might ultimately benefit the ARL mission needs to be articulated.

Assessment of the quality and ties to strategic Army objectives of the composite model project is difficult because development of the work is at such an early stage. The goal of creating a method for evaluation of optimal, feasible, and cost-effective fabrics is appropriate. The stated steps to improve and validate the model are essential but have not yet been taken. Examination of the composite model development to date leads to several strategic investment questions. Will the model represent knitted materials as well as woven? Will it be possible to validate this model for nonrepeatable experiments or experiments with a large QMU? Will the model be able to effectively represent laminates of materials?

The researchers on the project on tailored mechanisms for light armor ballistics articulated the goal: to develop a fundamental understanding of the deformation mechanisms and failure processes active under shock loading conditions for light armor materials such as aluminum and magnesium and then, using key discoveries, to control ballistic performance. Dynamic fracture testing, using plate impact assemblies, was conducted on as-received 1100-O aluminum cold-rolled to 30, 70, and 80 percent reduction to study the effects of microstructural evolution on spallation response. While an understanding of the relation between processing and microstructure and blast resistance for aluminum alloys is interesting physical metallurgy, its relation to improved armor was not defined. Further, the real purpose of this work or its value to the Army are unclear. After decades of working with metals such as aluminum for armor applications, the M134, Sheridan tank, and the Bradley fighting vehicle and of seeing their vulnerabilities to mines, rocket-propelled grenades, KE threats, and IEDs, it seems appropriate that ARL is finally looking to develop a fundamental understanding.

Humans in Extreme Ballistic Environments

The strategic, integrated system approaches to both the warrior injury assessment manikin (WIAMan) and humans in extreme ballistic environments seem headed toward significant near-term improvements in soldier protection. The fundamental underlying research was not described in detail, so it is not clear whether a breakthrough in the understanding—for example, of the cause(s) in traumatic brain injury—might lead to further breakthroughs in armor protection. Linkages to more modeling and simulation are encouraged as a way to facilitate more predictive performance capability development. Data on physical differences between male and female skeleton and body structure are now required to complete a female war fighter manikin development program.

The project on evaluation of the effects of blast and soldier protection measures on soldier performance faces several challenges. The research was not connected to research at other institutions (e.g., aviator helmet research across the Department of Defense (DoD) or sports helmet research) to foster the best innovation The metrics for physical performance were insufficiently defined, and no quantitative results were presented. There was no sign of substantive interactions with other institutions performing human performance modeling, testing, and simulation. Overall, what was presented was a series of demonstrations rather than a description of basic scientific research or engineering development. This line of investigation is important, and if the quantitative rigor of the work can be enhanced there is great potential for it to make a significant contribution to the field and to the engineering of soldier equipment.

The soft protection continuous-fiber woven composites project is strongly tied to yarn and fabric mechanics expertise, which is not available in-house but could be brought in through consultants. It was unclear how much deformation of the fabrics studied would be equivalent to fabric penetration; this is important for model validation. Understanding of the complex parameters that lead to fabric comfort is also expertise that does not exist in-house but it could be accessed by engaging consultants. A question arises: Would it be worthwhile for ARL to consider developing a broader in-house manufacturing capability to support related projects and equipment development in the future?

The project on an integrated approach for improving head protection against low-velocity impacts is focused on the need for energy dissipation over a broad range of low- velocity head impacts. This has resulted in the helmet pad investigation; it has also led to a novel shoulder-supported fixture and has called into question whether in the long term a helmet is the optimized solution for warfighters. This opens the door to new ideas for devices supported not only by the neck but also by or only by the shoulders or back (a space helmet) of the warfighter. Such approaches might help solve the low-velocity problem, might proved support for increased helmet weight necessitated by cameras and electronics, provide the basis for increased ballistic protection, and perhaps open the possibility of supporting more electronic functionality. Continued research in this area is encouraged. Linkages between this project and the modeling effort addressing the head/helmet system subjected to blast and ballistic loads are suggested as a positive avenue of research. Assessing the validity of neuro-network analysis is so challenging that it is not likely to produce short-term applications.

The project on applying survivability analysis to body armor decisions appears to be simply using an existing design tool for design analysis. The model did not produce quantitative data that were not self-evident. Being shot in the torso (or femoral artery) is bad, and the closer to the heart and lungs, the worse is the effect. Smaller armor protects less of the torso. Wearing protective shorts prevents groin area injuries more effectively than not wearing them. The case for applying computational models (instead of mere design rules) to these problems needs to be made much more strongly. ORCA does not appear to include modeling of armor and its effects; to simulate armor, the projectile velocity is simply attenuated based on data from experiments or other models. Coupling ORCA to ballistics models would extend its utility as a design tool. Integrating ORCA with some of the more physical models being developed in the WIAMan project efforts appear to be a fruitful avenue of research.

Computational Terminal Ballistics

The computational terminal ballistics presentation could have been made more effective by systematically addressing the modeling of kinetic energy penetrators, shaped-charge warheads, and EFPs in sequence—specifically, stressing the differences in their lethal penetration mechanisms and clarifying why each type of penetrator is effective against certain targets. This would have effectively set the stage for the blast and ballistic protection overview that followed the presentation. The fact that the ARL ballistics modeling uses approximately 87 percent of Army's high-performance computing (HPC) resources and approximately 65 percent of DoD resources overall is a serious challenge for future computational modeling. Although a plot of HPC resource growth was displayed, there was no analysis to show that the future computing capabilities would be adequate for ARL needs, much less new HPC needs that might emerge across the DoD enterprise.

For the project on vulnerability analysis of ground combat vehicles, more information on consideration of operational systems would have been helpful. Throughout many of the terminal ballistics briefings and posters, reducing the weight of combat vehicles through lighter armor and faster and more effective lower- caliber munitions was clearly central to ARL's strategic vision. However, it appeared there is not a clear set of objectives associated with the operational concept options, just an interest in providing options for performance versus size and weight to the requirements community. It seems that a common vision for cost and weight reduction, while at least maintaining capability would have provided a useful context for assessing this work and perhaps for the researchers.

The jet-induced-plasma characterization effort is simultaneously a high-risk and potentially high-payoff project. The physical characterization is still under way, so the potential payoff is a long way off. Even if successful and able to move to a higher level of technology readiness, the concept would necessarily be only one element of a layered capability. The project is an ongoing collaboration between ARL and Sandia. The results of experiments show signs of promise, but the phenomena have not yet been fully characterized, and continued modeling and validation are strongly encouraged.

If the EM squish phenomenon turns out to be promising, and if a follow-on exploration with a laboratory prototype shows it could be feasible, this approach can enhance other experimental effects. The effort is presently a numerical investigation using a model shown in another project to be lacking in a key area of physical characterization. Until the model is corrected and there is an understanding of the impact of the correction on the model's accuracy, this phenomenon needs to also be investigated experimentally. Even then, the relative improvement in advanced capability may not be as significant as predicted by the original concepts for the amount of additional equipment required.

The project on flow strength of polymers, covering the length scales from atomistic through continuum, would benefit by collaboration with existing polymer rheology and molecular modeling communities. The results need to be applied to anisotropic systems and other chemistries. Validation of the model against experimental data is crucial.

Both of the projects on reduced-order underbody blast modeling displayed many simplifications in the modeling. Further development may be necessary to expand the range of applicability of the modeling approach. There was no clear indication of specific progress on these projects since a review conducted by the ARLTAB in May 2012. Plans for model validation were not discussed, and plans for future accreditation by the U.S. Army Test and Evaluation Command were not satisfactorily explained.

The LF2XA explosive model parameterization approach is appropriate for ideal explosives; however, this explosive is likely a nonideal energetic material. Hence the variable reactive burn modeling needs to be regarded with skepticism. The calibration of this model was done using highly resolved CTH Eulerian computations.[2] However, the re-parameterization of the model in ALEGRA to replicate the CTH results may be the result of insufficient numerical resolution. Further verification of the modeling is required. Model calibration is linked to sustained planar shock experiments, and the applications to other shock loading conditions—that is, thin pulse or nonplanar projectile loading—may be far enough removed from the states of the model calibration conditions. This work follows a traditional approach in computation of shock-initiated reactive flow. Although there are recognized weaknesses in this approach, it may be sufficient for many studies.

The researchers working on novel penetrator efficiencies who look at segmented penetrators appear to understand the importance of developing credible baselines for comparison, and some results to date are promising with respect to achieving and maintain desired separation in flight and segment co-linearity during penetration. The potential benefits of segmented rods may become increasingly evident as impact velocities extend well beyond the current conventional ordnance velocity regime of ≤1,600 m/s. The work on extending the rod penetrator is also interesting, reflecting progress from earlier investigations into their potential. A particularly interesting means for extending the rod close to the target and locking the segments together has recently been transitioned to ARDEC for possible application in next-generation KE and DU replacement programs. As noted for segmented penetrators, it is imperative that credible baselines be established for performance comparisons to monolithic, nonextending rods, and validation to experiments is crucial. Strategic planning of S&T to support future Army needs for advanced KE is also crucial.

The armor modeling efforts described are important work and clearly will be helpful in guiding the development of ARL armor concepts while setting the stage for follow-on, well-defined, proof-of-concept experiments and subsequent advances. Finding measurable performance parameters so that the model predictions and experiments can be quantitatively compared is very important. Quantitative validation of the modeling, or at least of its ability to qualitatively predict changes in penetration resistance with changes in design parameter, is also seminal to this effort. Use of the results of the modeling to develop simpler—that is, much less computationally intensive—predictions of penetration resistance that can be used for vehicle-level assessments appears to be an important avenue to pursue.

Researchers on the project on armor material modeling and optimization stated that their goal was to determine which material properties have the most significant influence on ballistic performance of lightweight military specification metals; they noted that the goal will be realized by taking a design-of-experiments approach to modeling and simulation. Overall, the optimization effort seems sound, but to have an impact it will be important to translate the findings to the materials community for implementation.

OVERALL TECHNICAL QUALITY OF THE WORK

The overall quality of ARL's applied research and development is very high. There is, as realized by ARL management, a need to focus more on the basic research that will underlie future developments. ARL's existing S&T work in the ballistics area is very well served by the current Aberdeen Proving Grounds infrastructure and facilities. There was clear evidence of a speedy response to changing needs to support the warfighter with innovations in ballistic survivability and lethality. ARL's experimental programs concerning threats are quite detailed and demonstrate commendable knowledge of the evolving threats. The spectrum of armor design demonstrated a broad array of technical approaches and flexible and rapid response. ARL's staff is clearly motivated and competent, and all the staff members articulated

[2] CTH is a multimaterial, Eulerian, large deformation, strong shock wave, solid mechanics code developed at Sandia National Laboratories.

a well-defined line of sight from their research to the mission of the Laboratory and to the warfighter. All the briefings and poster presentations were well presented by the researchers. For the majority of posters, the work was state of the art and was properly juxtaposed with research at other institutions. For example, this aspect of the project on multiscale modeling of non-crystalline ceramics (glass) was impressive: The team is drawing on new results in nanotechnology, applying experimental equipment from geophysicists, and interacting with glass manufacturing R&D teams. In the Board's judgment, overall the basic science and the modeling of glass were first rate.

Many of the posters presented displayed in-depth collaborations with outside organizations, including other DoD laboratories, academia, and especially the national lnaboratories. ARL collaborated with the national laboratories on both the application of models/codes and the use of experimental facilities/instrumentation techniques. Some of the new analytical techniques and diagnostics developed to follow projectile penetration were very impressive. For example, the project described in the poster on the development of imaging and velocimetry techniques for impact studies used the Los Alamos National Laboratory's (LANL's) proton radiography facilities and applied LLNL's photon doppler velocimetry techniques. The observation of penetration phenomena at ever-smaller scales and faster times is crucial to the development of predictive modeling capability in the area of terminal ballistics and penetration mechanics. ARL is to be congratulated for seeking out the application of new diagnostic techniques to provide in situ data on penetrator–target interactions as a means to both discovery science and validation of the model for penetration mechanics. Additionally, the use of impedance spectroscopy and scanning probe microscopy for mapping grain boundaries in SiC-N was impressive.

Many of the principal investigators of research projects at ARL have working relationships with universities and national laboratories. This is praiseworthy and deserving of encouragement by management. Beyond that we see an opportunity to enrich the experience of the principal investigators by establishing further collaborations and short sabbaticals where they could become directly involved in cooperative research at allied institutions. One-to-one interactions on a daily basis would almost certainly enhance productivity and possibly generate new ideas for further productive research. A good starting point for such a sabbatical might be one or two weeks every year. Of course, the reverse arrangement could also benefit a visiting researcher.

The computational activities are in general well integrated into a large proportion of the research presented. Large, complex, and intensive calculations benefited from the use of externally developed, state-of-the-art code platforms, many developed at DOE. Many have been used in collaboration with other groups or national facilities, but some outstanding examples were developed in-house. There were extensive modeling efforts over a variety of length scales to follow penetrator–target interactions. Reduced-order modeling is an in-house-driven program that is clearly producing results for systems modeling. There was a clear demonstration of the interplay between materials and design of armor systems, which showed that close collaboration between materials, design, and computation efforts would be required to optimize performance.

ARL is making good use of funds allocated to Small Business Innovation Research (SBIR) projects. Several administrators and senior technical staff cited positive experiences with various sponsored projects. In one case, a small-business entity has demonstrated, for the first time, growth of single crystals of aluminum oxynitride. This achievement has opened up exciting opportunities for basic research at ARL. It appears that the new processing technology can also be applied to other difficult-to-process materials. ARO also gains substantial leveraging from its Small Business Technology Transfer (STTR) projects.

3

Human Sciences: Simulation and Training Technology

INTRODUCTION

The Panel on Human Sciences at the Army Research Laboratory conducted its review of ARL's Simulation and Training Technology Center (STTC) at Orlando, Florida, on June 18-20, 2013. This chapter evaluates that work, recognizing that it represents only a portion of ARL's portfolio of core competency in human sciences technology.

Broadly stated, the mission of STTC is to enhance readiness through research and development of applied simulation technologies for learning, training, testing, and mission rehearsal. The goal is to understand and opportunistically integrate the human science implications of these activities in order to optimize the behavior of individual soldiers and of small units or teams. One of the goals is to understand and develop immersive technologies that are both operationally effective and cost effective for training and mission rehearsal, and to transition the next generation of modeling and simulation technologies to the future.

The STTC research program has four components:

1. *Adaptive Training Technologies Program*. Its objective is to design, develop, apply, and assess artificially intelligent agent technologies—such as adaptive tutoring and virtual human tools and methods—to enhance training effectiveness and reduce costs. An important emphasis is on developing tools that allow others—researchers, instructional designers, training developers, and trainers—to efficiently author new training modules so that artificial tutors can be created for different training needs as they arise. The effort to develop a broadly applicable framework has produced the STTC's generalized intelligent framework of tutoring (GIFT), which is a useful tool for the development and evaluation of intelligent training systems.
2. *Synthetic Natural Environments Program*. Its objective is to enhance physics-based synthetic environment modeling, with a particular emphasis on dynamic effects such as changes in weather and lighting.
3. *Training Applications.* The objective of this work is to create and test physical models and software-based simulations for diverse training applications such as medical triage, dismounted soldier operations, or training on specific ground platforms.
4. *The Advanced Distributed Simulation Program*. Its objective is to conduct R&D work in the area of software design to create a common core infrastructure and toolset to enable distributed and collaborative services in modeling and simulation. The long-term goal is to perform R&D aimed at integrated software architecture to support modeling and simulation across the Human Research and Engineering Directorate (HRED) and beyond.

This assessment is the Board's first in-depth review of the STTC since its merger with the ARL's HRED in 2010. During the 2011-2012 review cycle, several STTC programs were presented as part of a broader review at the ARL HRED at Aberdeen Proving Ground, Maryland. The Board's most recent 2011-2012 report observed that the integration of the STTC into HRED creates great opportunities for human factors influence on STTC products and STTC enhancements of traditional HRED endeavors.

The report suggested that the STTC and HRED increase their focus on human factors in training and continue to integrate STTC technical competencies with HRED skills in human factors research.

While some progress toward this goal was evident in the present assessment, the merger of STTC with HRED needs to be taken to the next level, with greater emphasis on integration of human sciences. The design and development of effective training systems is an inherently interdisciplinary enterprise necessitating an early and balanced collaboration of computer science and human science inputs.

The installation of the STTC commander as deputy director of HRED is a commendable, vital step to integrating two strong organizational capabilities and cultures to the benefit of both ARL and the Army.

ACCOMPLISHMENTS AND ADVANCEMENTS

The STTC mission is to improve training efficiency and effectiveness through technology. The projects briefed reflect an ongoing emphasis on training technology for the dismounted soldier that is arguably the most difficult technical challenge and the area with greatest need in the Army today and the foreseeable future.

STTC is tackling a number of very challenging technical problems in training technology such as how to make tutoring systems adaptive to individual learners, how to best manage instructional experiences, how to make synthetic entities behave more intelligently in training simulations, and how to make training simulations more interoperable.

Many areas pursued by the synthetic natural environments technology group have great potential to set standards that other programs (and other Services) can follow. These areas include simulation in the cloud and terrestrial databases. The advanced distributed simulation (ADS) group therefore has a unique opportunity to generate guidelines or protocols for future developments across the DoD in these areas. For example, documenting the methodology, process, definitions, performance metrics, and validation tests for running simulations in the cloud, and identifying standards and technology to accomplish this, would establish a standard approach for the community.

The STTC work is significant and valuable in specific application domains (e.g., simulations of battlefield medical situations), as well as in the design of general tools for simulation (e.g., the generalized intelligent framework for tutoring [GIFT]) to make it possible for others to rapidly create new training modules for areas with new content. Laudable progress has been made to date in the development of GIFT and in the incorporation of this framework within the computer game Virtual Battle Space II being used by the Army for training.

OPPORTUNITIES AND CHALLENGES

General Opportunities and Challenges

The Role of Human Sciences

Training simulation and human behavior representation are inherently inter-disciplinary R&D domains that would clearly benefit from the integration and balancing of insights and the connection of ideas from the diverse perspectives of the computer sciences and the human sciences. It is evident that STTC has its strong suit in computer sciences. The paucity of the human science research presented to the review panel made it equally evident that, as it stands, STTC is weak in this area—for example, cognitive and perceptual psychology and human factors—and is losing the potential benefits that often come from the fusion of alternative technical frameworks and approaches driven by human sciences. For example, human sciences identify a wealth of variables and data in the areas of sensation and perception (visual, auditory, tactile, olfactory); attention; problem solving and decision making; learning, motivation;

emotion and mood, social factors, human workload; human factors/ergonomics; psychometrics; individual differences; and cognitive modeling—all relevant to immersive learning, adaptive tutoring, performance in synthetic environments, and assessment of performance.

The merger of STTC with HRED was a very well-conceived decision by Army management that needs to play out more effectively than it has to this point. The main challenge lies in the integration of STTC into HRED in a manner that is useful to both. The human sciences, available more generally at HRED, need to be considered early in the requirements phase and then throughout the design of simulation and training systems. The training technologies being developed have significant implications for humans and their ability to acquire task-critical skills and to become proficient performers. It is difficult to design training software without an appropriate understanding of the instructional objectives and human response to the training environment. For example, how can one know how much fidelity is needed in different aspects of the simulation without understanding the impact of fidelity on learning and retention? Other vital areas that would benefit from considering human sciences include expertise and the elicitation of expert knowledge, identification of training objectives, feedback, team cognition and learning, student and expert models, learning processes, transfer, and retention.

Insular Community

As described above, the technical challenges faced by STTC are multidisciplinary. Though there is a valuable concentration of simulation and training expertise in Orlando, STTC needs to engage and leverage the broader national and international simulation and training research communities as well. A large component of the STTC R&D staff appears to be bred and trained by a handful of local institutions. As a result, they appear to be somewhat insular with respect to the communities of practice from which they draw. The ARL STTC team needs to consciously recruit at all levels from outside "Team Orlando." Constraining recruiting and hiring to the military, local industry, and local universities will lead to isolation from ideas current in the broader S&T community. While there is evidence of senior leadership participating in occasional international conferences, wider engagement of the research staff with the broader national and international research community through publications, invited speakers, scholars in residence, conferences, internships, and postdoctorate positions is warranted.

The problems being tackled by STTC are large, complex, important, and currently relevant to the modeling and simulation community. However, there are also many researchers working on these issues in academia and in other military laboratories outside the STTC environment. STTC researchers need to clearly define and focus their efforts within the broader scientific community, identifying precisely where they expect to advance the state of the art. For the original research presented, it was not clear where the research fit (or was framed) within the broad base of existing scientific literature. Although some work was described as applied research, the value case was not established with respect to specific Army training applications and problems.

STTC is in a unique position to enable collaboration between military-subject-matter experts, trainers, and trainees with computer scientists and simulation specialists. Developing training technology with specific users in mind and developing an in-depth understanding of their needs (as was done by STTC in the medical simulation area) would lead to more focused research and more useful results. Some of the ways to accomplish this might include applying human factors models of task requirements and human capabilities/limitations, identifying relevant individual differences, testing prototypes, soliciting feedback from trainees and subject-matter experts, and collaborating on design and testing. It is important to maximize opportunities to engage with military-subject-matter experts and users at training centers, battle labs, and similar venues. While current budgetary and policy constraints are self-evident, external engagement needs to be a management priority.

Relationship with the Institute for Creative Technology

The STTC is the government program manager for a University Affiliated Research Center, the Institute for Creative Technology (ICT) at the University of Southern California. The ICT receives 100 percent of the STTC basic research (6.1) funding and needs to be integral in addressing some of the STTC's basic research questions. It was not clear, for example, how STTC requirements are communicated to ICT or how ideas feed down from ICT to STTC. This is obviously a relationship that can be exploited to broaden perspectives in both directions: people closer to the user community and people closer to research. The ICT is, however, assessed by a separate Army assessment board, and the ARLTAB was not asked to review the ICT.

Publications

STTC's output of peer-reviewed publications is low. Aside from the work presented in the area of adaptive tutoring, which identified a half dozen reports in venues other than Defense-related conferences, STTC presenters identified almost no publications yielded from the work presented. Publications are more than a simple indicant of quality. Active publication systemically drives quality in S&T cultures and organizations. Engagement in the publication process subjects the research to rigorous review, generally improving it and increasing quality. Furthermore, publications encourage project completion deadlines, polished results, and thoughts about the next steps in R&D. They are also a venue to increase visibility in the research community.

It is important that STTC aim to publish in high-quality venues—for example, in top journals and at conferences that require full papers, where each paper is reviewed by two to four outside reviewers (not on the program committee). Its papers could be indexed in catalogues and collections that are available to students and researchers (e.g., *IEEE Explore* and *ACM Digital Library*).

Observations on Individual Projects

Immersive Learning and Intelligent Tutoring

The goal of the Learning in Intelligent Tutoring Environments (LITE) group is to develop an adaptive, computer-based tutoring system that selects optimal instructional strategies to meet the specific learning needs of individuals or teams; assesses trainee attributes (e.g., progress, behaviors, and physiology); uses these attributes to classify states and predict learning outcomes (e.g., performance, skill acquisition, and retention); and then adapts the instruction to influence learning. This is clearly an important and challenging problem for the STTC, and the general approach the LITE group has taken to the problem seems to fit well with the broader mission of the STTC. The approach is to develop a flexible, modular system that can be used by individuals who are not computer experts to support a broad range of different point-of-need training challenges.

There are some challenges for this broad area. First, the complexity of the problem being tackled almost certainly requires a multidisciplinary approach. As discussed earlier, there was little evidence of expertise in the areas of human cognition, attention, motivation, emotion, or perception outside those listed as external "advisors" to the program. These areas of expertise need to be intimately involved in all stages of this type of research. Secondly, it appears that little progress has been made on the immersive aspect of tutoring. From the presentations it was obvious that a large investment in effort has already been made in investigating a few specific factors such as voice-of-God (i.e., a computer voice, not identified with a virtual team member or instructor, provides feedback to the trainee) versus socially grounded tutoring, windowed versus embedded tutoring, and navigation by mouse versus joystick. However, it was not clear why these particular factors have taken on such importance in light of the many other factors that are more likely to enhance the immersive experience. Among these would be sensory inputs (full field of vision, auditory stimuli, tactile stimuli, and, for some applications, olfactory and gustatory stimuli) that provide cues and feedback relevant to a trainee's decisions or actions and that facilitate the transfer of training to real-world situations. Another challenge and area of concern was the lack of attention to the issue of readiness for general and online training. The assessment of learner readiness, temperament, and personality has been shown to be a critical step in the pedagogical development of training materials; given the normal and expected diversity in learner backgrounds, it deserves to be a priority.

Adaptive Tutoring Research

The adaptive tutoring research initiative is focused on tutoring technologies that can equal or exceed skilled classroom instruction or skilled human tutors. The focus on tutoring technologies tailors learning activities to the state of the learner or group of learners using adaptive machine-learning methods. Overall, the vision for this research is very ambitious, and the issues being addressed are very important, such as modeling cognitive and affective states, instructional management, and the rapid development of expert models. The research group has apparently reviewed a wide range of existing work in intelligent tutoring, is building on what exists, and seems to be grounded in both empirical and theoretical work. The research studies presented were focused on motivational issues related to stress or boredom that might be translatable to dismounted individuals in complex and team missions. What were not clearly stated was how the R&D agenda is being driven by specific Army training needs and how some of the ICT work on training is being incorporated.

The domain of adaptive tutoring research is enormous. The research program would benefit from a tactical evaluation and staging of subgoals. For example, to what degree should the focus be on tutoring individuals in specific skills versus tutoring and training platforms for multiple agents or teams? The issues, solutions, and products could be quite different. Discussion with the STTC group indicated that the priority was on team training. However, the product cited as very successful was a mobile improvised explosive device (IED) trainer—primarily for the training of individuals using preprogrammed training regimens.

Another issue is the degree of simulation fidelity required for successful adaptive tutoring. The demonstrations implicitly assumed that very high visual fidelity is desirable and will improve effectiveness of training. However, high-fidelity visual displays may not be the limiting aspect of tutoring environments where joysticks or other simplified tools of action are used to, for example, replicate the physical movements of the agents. If the idea is to train sequences of behavior or logical decision trees of a mission plan, then perhaps visual fidelity, which may be too expensive, could be reduced in favor of focusing on training properties more critical to transfer to real missions. This is yet another illustration of the need for integrating more human sciences into the R&D effort.

A third issue is whether to focus on training for general situations or for preparatory rehearsals for actual missions. Training for general scenarios might be very useful—for example, to practice responses to low-probability event structures that would infrequently be encountered in a real situation yet must be among the trained repertoire for robust performance. In this case, there is little necessity for integration of real 3D terrain mapping or urban mapping of specific locations. On the other hand, if the goal is a preparatory rehearsal for a mission, software support that is effective in integrating real-world mapping data may be quite important.

Effective adaptive tutoring is likely to increase the interplay between computer science approaches and human science specialists in relation to the delivery of sensory inputs, the biosensing of the emotional or motivational state of the individual, learning theory, and adaptive testing. It would be useful to identify several high-priority, prototypical applications as benchmarks for testing development. The project must incorporate human testing and evaluation early in the design stage when deciding about where to spend resources in the development of technological systems so as to maximize human learning and performance.

Overall, this group is cognizant of the need to integrate knowledge from the existing literature and has done a fine job engaging the academic side of intelligent tutoring at well-selected conference venues that is likely to provide them far more rigorous reviews than DoD conferences. It has been effective in establishing a Board of Advisors made up of distinguished subject-matter experts from industry and academia. These advisors can serve them well if effectively used as critical and constructive reviewers of their ongoing and planned research. Overall, this team exhibited a strong sense of teamwork and passion for the research as well as an attitude strongly supportive of the development of technical skills and the education of junior scientific members.

Generalized Intelligent Framework of Tutoring

The GIFT framework is a laudable effort to establish a general framework for intelligent tutoring. The GIFT demonstration illustrated a computational platform early in development that ambitiously aims to provide a structured environment for the authoring and managing of individual and complex multi-actor team tutoring by individuals with less specialized technical and programming skill. The framework was outlined, but no details were presented on its significant components, such as the expert or student models or the selections of instruction. A wide range of sensors and the limitations of those sensors were discussed. However, there was no justification for the sensors that were selected with respect to their relevance to learning the task at hand. For example, is a full-motion platform that enables the trainee to experience walking in the game justified if a joystick is adequate for what the trainee needs to experience for the task at hand?

GIFT has potential to become a useful and important framework for embedding results from the center's research and solving some of the Army's training problems. It is also early enough in development to reconsider its design priorities—that is, to consider implementing a truly adaptive assessment and training system within a pedagogical model that could better drive the system in the direction of the tutoring, training, and simulation problems, which are the highest priority of the Army.

An alternative might be to consider studying and integrating truly adaptive aspects of existing tutoring products in domains such as mathematics and knowledge space theory. These applications map dependencies between target skills or knowledge (skill A generally precedes skill B) and use probabilistic testing to first assess current knowledge and performance and then to determine what might best be trained next. The knowledge spaces of the military training applications may be "flatter" and less complex than domains in mathematics, but they might still exhibit strong content structure. Knowledge structure approaches, if applicable, could provide important information about readiness to learn subskills that could be critical in effective use of time on training. Trainee performance data may provide validation of content structure analyses and need to be considered an important tool in product development. Further, to the extent that many aspects of military training have already been codified in procedures and sequences of training activities, there may already exist starting structures for defining the relevant content domains.

Explicit Feedback with Game-Based Training

Current game environments provide only implicit feedback. To enable explicit feedback, STTC has embedded intelligent tutoring functions in games through embodied pedagogical agents (EPAs). This represents an effective use of an existing technology investment (Virtual Battlespace 2 [VBS2]) to perform studies and collect data. Since the VBS2 gaming system is becoming a more prevalent in the

Army, integrating GIFT with it is a good strategic move for future tutoring, because trainees will have a common platform they can use for a range of tasks. The integration of GIFT enables them to collect information in real time for after-action review and to correct trainees in real time so they do not repeat erroneous behavior.

The EPA study presented was an excellent example of the use of the human sciences to design intelligent tutors. The study was grounded in social cognitive theory and was a simple, well-designed test of the increased efficacy of embodied agents in providing feedback. EPAs were used as instructors or team members from different sources (e.g., GIFT or embedded in the game). The idea of GIFT turning a player in the game into a tutor appears to be a very natural way for a trainee to learn—that is, from other teammates (albeit virtual). In this study, simple verbal feedback was about as effective as embodied agents feedback—simplifying the demand characteristics of instructional game design in contrast to the literature, which suggests a larger impact for embodied sources. However, it may still be that an actual embodied agent (e.g., a military expert) could be more effective in, say, transfer, suggesting the need for further study.

Modeling Learner Mood in Real Time Through Biosensors for Intelligent Tutoring Improvements

This study is based on the idea that if the stress levels of individuals could be tracked and classified in real time, then training regimens could be monitored to advance training without triggering a stress response. The study included a number of biomarker measurement devices, including sonar (for distance measurements), a device for measuring pupillary response of the eye, a heart rate sensor, a higher-end electroencephalogram (EEG) system, and an inexpensive, 14-channel, simple EEG system. Trainees completed tasks and periodically self-reported their stress state. Several data-mining techniques, including simple regression and several machine-learning clustering techniques, were tested for their ability to learn to classify the biosensor data using the trainee rating as the target. This is essentially a test of the success of several different classification algorithms. The results had yet to be tested with the usual forms of classification cross-validation, nor had the quality of classification been determined with different subsets of biosensor inputs, highly relevant if the aim is to classify trainee reactions based on small numbers of inexpensive sensors.

The development of simple biosensor-based assessments of stress has the potential to make useful contributions to monitoring trainees. The project would benefit from the inclusion of human science specialists in physiological response monitoring for EEG and heart rate and pupillary dilation to place the data mining of biosensor measures for classification within large literatures related to human physiological responses.

Synthetic Natural Environments

The research programs in synthetic natural environments are focused on computer technical developments that will generate large-scale, realistic, immersive environments. The researchers cite the need to integrate 3D information about environments and the detailed information required to simulate urban warfare environments in high resolution. The goal is to incorporate and simulate weapons and machine impacts in these environments, which requires sophisticated models of the physical world. For example, models of building strengths and stressors in the urban environment are necessary to implement realistic consequences of simulated interventions.

Real-Time Dynamic Physical Effects in Army Synthetic Environments

The project demonstration in this area clearly illustrated the need for faster computations in order to create useful environments with realistic physical effects. There are interesting elements to this work. One is the ability to adjust fragment grid size to achieve performance. Another is accepting (for now) simpler models (without drag) to achieve subsecond results with full knowledge that more powerful processors will allow more faithful models in the future. However, the approaches presented did not take advantage of current and newer hardware architectures, such as graphics processing units (GPUs). All the work presented was based on traditional central processing unit algorithms. STTC needs to advance its research in this area toward the more general trend in the computing community if it wants to remain a leading research group in this discipline.

Terrain Generation

It was indicated that the current state of the art of terrain database generation is costly, slow, and complex and not up to the challenge posed by the need to dynamically represent high-resolution urban terrain. The ambitious challenge addressed by this STTC effort is the assumed need for effective and low-cost representations of terrestrial line of sight; dismounted and mounted maneuver; weapons effects; close air support; intelligence, surveillance, and reconnaissance (ISR); and communications. However, it was not fully evident that the fundamental requirements of tactically relevant ground force simulation are best served by the stated objectives: to minimize cost, complexity, storage, and licensing fees. Perhaps it would have been more illuminating if the case had been based on a critical evaluation of contemporary practice against the inherent interoperability requirements of live, virtual, constructive, and gaming simulation.

Cited plans for future research included rapid database generation for mission planning, exploitation of comprehensive feature extraction from LiDAR[1] and hyperspectral imagery, and real-time processing of aerial- and ground-collected data. There was no evidence of STTC expertise in this area; STTC needs to pursue aggressive evaluation and exploitation of contemporary geospatial data sources such as Urban Feature Data Level 3, Specialized Urban Topographic Data Store, and Multinational Geospatial Co-production Program products from the National Geospatial-Intelligence Agency or the Homeland Security Infrastructure Program. Similar to the presentations on real-time dynamic physical effects in Army synthetic environments, there was little discussion about how newer hardware architectures could help with this work. The underlying methods were grounded in more conventional computing and data management approaches.

Human Representation

STTC reported on work to improve the physical representations of humans—for example, gestures and movements in distributed simulation, which are a serious shortcoming in current systems. However, the progress achieved since 2010 was not made evident.

The reported work with Soar, which is aimed at enhancing the intelligence of agents in order to enable consistent social cultural behaviors, is commendable.[2] However, the degree of social and behavioral realism for synthetic forces continues to be a challenge and a concern. The complex challenge of modeling creditable tactical behavior in computer-generated forces requires ongoing collaboration and

[1] LiDAR (also written Lidar or LIDAR) is a remote sensing technology that measures distance by illuminating a target with a laser and analyzing the reflected light. The term "lidar" comes from combining the words light and radar.

[2] Soar is a cognitive architecture used to model different aspects of human behavior.

engagement between military subject-matter experts, computer scientists, and human scientists. In particular, there needs to be explicit guidance from cognitive and behavioral scientists on the level of realism and fidelity in training applications. For example, in training simulations that involve interaction of avatars with foreign agents, emphasis on the facial expressions, pupil dilation, body language, and other features are paramount; if resources are limited, it is important to scale back other less critical features of the environment.

Future research areas in synthetic natural environments cited by STTC included improved immersive capabilities involving acoustics and tactile feedback support (haptics). Distributed simulation systems as early as SIMNET achieved considerable perceptual stimuli from dynamic acoustic cues (e.g., munitions effects, vehicle operations). Such auditory inputs are critical for monitoring and maintaining situation awareness. Background sounds are sometimes a critical cue. For example, lack of normal activity played a big role in alerting experienced soldiers to potential terrorist threats in Afghanistan and Iraq. STTC's stated intention to pursue investments in localized acoustic, haptic, and olfactory stimuli is appropriate.

Advanced Distributed Simulation Research

Overall, the challenges addressed by the Advanced Distributed Simulation (ADS) research group are of great importance to the simulation community and the Army training mission. This group has very strong skills and backgrounds in computer science and software engineering, which gives it a great foundation for designing and building stable, well-engineered simulation systems. Computing technology is changing rapidly, and the ADS group needs to track and leverage leading advances in industry because it will not be able to accomplish the needed advances on its own. The STTC group has developed some important strategic relationships with the information and communications industry (e.g., Intel). Moreover, the shared computing infrastructure in Research Park is a great resource to leverage for managing costs.

The ADS group has a good appreciation of existing standards, commercial off-the-shelf (COTS) technology, and open source tools that it can leverage to enable it to focus on new developments that are needed. Examples of this include modeling and simulation (M&S) standards from the Simulation Interoperability Standards Organization, virtualization, cloud computing infrastructure, and others. However, keeping up with technology evolution will be a continuing challenge. For example, there was no mention of work with GPUs or of any intent to implement parallelization or to leverage multicore processors. Also, there was no mention of big data, analytics, or computational social science, all of which are relevant to the work the group is pursuing. It could be that partners in Research Park with whom it is collaborating already cover these technologies. Having a technology roadmap would help ADS to determine which partners to leverage for those technologies important to achieving program objectives.

Overall, the ADS group appears to be staying reasonably abreast of research in the simulation community. This gives it an appreciation of open technology issues that need to be addressed, such as the behavior of semiautomated forces, simulation in the cloud, and realistic locomotion in virtual environments. The group's publications appear to be mainly in connection with nonacademic, nonrefereed conferences. It needs to branch out to academic-type conferences, where the review process is more considered and thorough. This will also expose it to a broader range of work in the M&S and computing community beyond that being accomplished in Orlando and at the University of Central Florida.

The Science Behind Executable Architecture Systems Engineering

The Executable Architecture Systems Engineering (EASE) project is tackling some very difficult and important problems in training simulation interoperability and is focused creating an easy-to-use environment for running simulations in the cloud. While STTC is not developing any of these simulations, it is developing the approach and methodology to easily set up and run the simulation.

While this is recognized as an important problem to resolve, the group did not present clear evidence that the approach taken can succeed given the scale and complexity of the experience provided by real training environments. The presentation's high level of abstraction made it difficult to determine how much of the work is focused on infrastructure and how much on simulation interoperability issues. For example, simply having an infrastructure that enables simulation to communicate is not the same as semantic interoperability. It appears that this has been initially designed for a very limited, known set of simulations to simplify the overall problem. However, it was not clear whether there is intent to expand the set of simulations to lesser-known systems, and, if there is, whether the project's methodology is capable of addressing these.

One of the features of the proposed system is to provide users with a simple interface where they can answer questions about what they are trying to accomplish (e.g., purpose, scenario), after which the simulations are automatically set up in the cloud. One such question proposed for presentation to the user concerned the necessary level of fidelity. Given how fidelity is defined and mapped to a given simulation, it could be very challenging for a user to know what fidelity is needed from a training perspective.

This area of research opens for STTC a real and strong opportunity to lead future developments in synthetic natural environments by using its research efforts to generate guidelines and protocols on how simulation software needs to be developed, aimed at the long-term goal of an integrated infrastructure in modeling and simulation.

Training Applications

Live Training Research Objectives

This project was focused on potential technological improvements in the widely used laser tag live training systems. Challenges exist, for example, with respect to the extension of firing trajectories from direct line of sight and improvements in positioning information relative to the target. Current weaponry increasingly uses nonlinear trajectory targeting that requires computational solutions rather than direct sensing. A related goal is to more clearly understand which parts of targets have been hit, and this requires extended sensor arrays and damage models that might predict survivability of human agents or functionality of larger-scale equipment such as tanks or vehicles.

The importance of this work to the Army was well communicated, particularly with respect to the importance of identifying and avoiding friendly fire incidents. Future developments stemming from this project could provide identification information for friendly agents and a processing system that would support large-scale, complex, multi-agent situations.

These projects were tightly coupled with widely used training technologies, and the described projected improvements in next-generation modules and sensor arrays involve fairly straightforward, though important, technology upgrades. This technological development track needs to incorporate human science and human factors input to effectively address questions such as, Which functions should be assigned to the human and which should be automated? When should human judgment override computer-aided decision? How should such decisions be communicated? Answers to such questions will provide boundary conditions for any new systems.

Next-Generation Common Multiple Integrated Laser Engagement System

This work deals with the specific issue of weapons' targeting precision using laser propagation. The presentation focused on the laser propagation and signal detection science and did not address the human user (shooter and victim) element of the system or how this might play into training. The research team comprises engineers without representation from the human factors perspective. This was evidenced by the quest to achieve realism without addressing the assumptions underlying its value to training.

Dismounted Soldier Training Research Objectives

The objective of this advanced technology development (6.3-level R&D) program is to support TRADOC Warfighter Objectives to improve virtual immersion, locomotion, and avatar intelligence for training dismounted soldiers. STTC is addressing important challenges for the effective use of mixed reality, including the volume and weight of backpack needed to do the computation for the training, locomotion using joystick interfaces, and comfort issues with heads-up displays. These systems raise many questions about what aspects are necessary to simulate from a training effectiveness perspective. For example, what are the implications of not representing with adequate fidelity the auditory, tactile, or olfactory sensory cues in training and rehearsal activities?

Improving the intelligence and realism of synthetic entities (e.g., opposing force) in simulations and training games is an important issue and has generated a great deal of research. As it did for the other projects it presented, STTC conveyed the assumption that realism is a reasonable goal for its own sake and worth the cost. A huge issue from the human sciences perspective is this: What level of realism suffices in time of high stress, particularly tempo-related stress, where high quality may not be possible owing to sensor and computational constraints such as dynamically changing terrain? Will the current warfighters insist on videogame visual quality in a training system if training stress can be raised to approximate that of action in the field? How important is simulating more realistic motor performances, fatigue, or stress through general levels of noise and other inputs? What is good enough in which situations?

Medical Simulation for Training Research Objectives

The medical simulation technologies used in training for medical interventions provided a model case for front-end analysis of downstream application needs and a model of the use of technology to provide suitable training and general exposure to individual medical personnel. This "full recurrent cycle" process—applying, sequentially and recursively, assessment, planning, implementation, and reassessment—seemed a model that could be extended to other research programs.

Several of the demonstrations entailed very detailed renderings of hypothetical environments. This raised interesting questions about whether these are necessary for effective training and whether they might constrain training to these detailed representations and, in effect, reduce the transfer of training. Evidence was not presented to permit determination of whether joystick interfaces are sufficient or whether more emphasis should be placed the on natural sensing of motions and their translation into virtual reality environments.

The STTC work in this area appeared strongly linked to actual needs of the medical instruction community. Researchers said that they had had to find the gaps in needs and knowledge themselves. Of particular note are the efforts this group made to observe at the Multiple Amputation Trauma Trainer at the Army Medical Center in order to better capture the relevant parameters for their simulation scenarios. As a result, they developed strong ties to the medical training community, understood its needs (e.g., instructors' overload), and developed training systems that have been successfully transitioned to field use for medical training.

Use of Holography in Medical Training

This project examined the requirements for holographic representations of the human body for medical training. This is a new and potentially expensive technology that needs to be weighed against alternative technologies (e.g., motion-based animations of human body and brain systems now available in inexpensive applications for cell phones or iPads) that could prove as effective as or even more effective than holography from a cost and training perspective.

Incorporating odor into medical training simulations is a relevant consideration, because numerous studies have revealed that unexpected or unpleasant odors can be a significant distraction in the field. Prior training that includes exposure to malodors that could be encountered is a way to immunize the warfighter or medic against the loss of concentration or attention as well as to minimize the likelihood that the odors can become associated with stress and later serve as triggers for trauma. There is also significant benefit in augmenting training by multisensory information beyond the medical domain, because warfighters can encounter unusual, unexpected, or unpleasant odors in a variety of deployment settings.

Virtual Locomotion Concepts and Metrics Study

The stated objective of the work is to achieve natural and humanlike locomotion in virtual space. The study team seemed well abreast of the current state of this technology and related research, and it has been able to effectively create a complex, real experimental condition against which to compare the virtual techniques. The experimental conditions included a good selection of movement gestures, including jumping, squatting, crawling, and climbing; the data show that the encumbrance of real gear makes some gestures difficult, just as it makes some real locomotion hard. It is well documented in the literature that users want to be able to move in any direction while gazing in a different direction. Locomotion techniques that do not allow this separation of view direction and movement direction are, in a sense, noncompliant with respect to best practices and ought not be included in testing designed to find the most natural locomotion technique.

High-Fidelity Character Autonomy for Virtual Small-Unit Training

This work was presented using realistic dynamic behaviors and intelligent decision making based on situational context and the decisions made by other players. They are using the Joint Simulation Bus developed by ONR to allow connectivity with different game engines. The game environment is a potential constraint limited by the product's behavior (i.e., the conceptual model established for the game world). Another potential constraint was the selection and use of a legacy system and architecture that were originally developed based on different assumptions and technology than are currently available. Therefore, it was not clear how this product would benefit training.

OVERALL TECHNICAL QUALITY OF THE WORK

STTC has historic strength in computer science and engineering, and it has developed a number of successful technology-enhanced training products. The ARLTAB's assessment recognized these accomplishments and also examined how the performance of the STTC might be improved by integrating additional scientific expertise, exposure to new or alternative scientific approaches, and tactical consideration and staging of project goals.

Overall, STTC has a clear and substantive mission with many important and unique objectives. The Orlando-based leadership and scientific research groups exhibited a high level of professionalism, commitment to high technical standards in their projects, and a broad appreciation of their role in enhancing military and human outcomes. The esprit de corps and desire to integrate innovative and effective research strategies were notable in both research teams and leadership. Investment in professional development and training of junior scientists was a priority of the program. The STTC is an excellent research unit that embodies high technical standards and strong operational attitude.

Much of the work presented represents an interesting intersection of M&S with computer science. In this context computer science is broader than software development: It includes artificial intelligence, intelligent systems, parallel and distributed systems, social media, online learning communities, digital media and gaming, big data and analytics, computing performance, networking, graphics, and visualization. Many research groups at STTC tend to focus on a specific problem domain and simply use computer science disciplines to create better simulations. Owing to the breadth of work being done at STTC, the staff members are in a unique position to establish themselves as one of the leading research groups working at the intersection of M&S and computer science. While basic research is done by ICT, STTC can (and needs to make the effort to) still integrate research from ICT and others, as well as innovate in the application of these technologies into real-world programs. This would require achieving a broader view of the intersection of computer science and M&S and creating a technology roadmap and strategy for how to accomplish this goal.

The research presented by STTC would, to varying degrees, benefit from integrating human science experts (e.g. human factors and cognitive scientists and social psychologists) into the research teams. For example, one of the goals of the simulation technology group is to push the envelope of simulator fidelity, whether it is the number of live users using the system or the physical realism of the system. Some of these questions are mostly technical problems, but in many instances they could benefit from human science experts. For example, knowledge about human perceptual limitations could steer simulator designs and, in turn, not waste bandwidth pushing unnecessary data. Conversely, it could also reveal areas where computational resources should be concentrated (e.g., in auditory realism). Related to this is the idea of satisficing in simulator design. That is, what level of fidelity is adequate for satisfactory training to occur? Overall, some of the areas could benefit from a systems-engineering approach that views the simulator not just as hardware and software but as a complete system of interdependent elements that include human operators.

The incorporation of human science approaches and human science professionals in the research teams and in the specification of internal standards could enhance the human science expertise of the researchers, augment functionally engaged scientific advisory arrangements, and expand training opportunities for developing senior and junior scientists.

A strong related suggestion is that STTC work to improve the quality of its user study designs, including design of the data analysis. The studies it conducts are costly, and it is vital to be certain that they are both gathering sufficient data on the critical variables of interest and performing well-designed statistical analyses. Technologists are not trained experimenters and will likely benefit from expertise identifying proper independent and dependent variables, measures, and study design elements such as between- or within-subject, needed sample size, and elimination (or mitigation) of confounders. This is another area where closer engagement by human science researchers can pay off, because these subject-matter experts are generally well-trained in experimental design and statistical analysis of both quantitative and qualitative data.

4

Human Sciences: Translational Neuroscience

INTRODUCTION

The Panel on Human Sciences at the Army Research Laboratory (ARL) conducted its review of ARL's translational neuroscience program at Aberdeen, Maryland, on June 11-13, 2013. This chapter provides an evaluation of that work, recognizing that it represents only a portion of ARL's human sciences core technology competency portfolio.

The goal of the translational neuroscience (TN) program is to integrate modern neuroscience with human factors, psychology, and engineering to enhance the understanding of soldier function and behavior in complex operational settings. TN, as it is defined, is a unique and important effort whose objectives, if successfully accomplished, could be a game changer for soldier and mission effectiveness.

TN has concentrated its efforts on three research thrusts:

1. *Brain–computer interaction (BCI) technologies.* Enable mutually adaptive brain–computer interaction technologies for improving soldier-system performance.
2. *Real-world neuroimaging*. Assess those aspects of brain function that can be usefully monitored outside of the laboratory setting and assess and/or develop the technologies that are best adapted for this purpose.
3. *Brain structure–function couplings.* Translate knowledge of differences in individuals' brain structure and function to understand and predict differences in task performance.

From 2009 through 2013, the TN group made significant gains in publication rates and quality (from 16 publications in 2009 to 44 in 2013, including an increase in publications in peer-reviewed journals from 6 in 2009 to 17 in 2013); numbers of postdoctoral researchers (from 2 in 2009 to 11 in 2013); outreach and mentoring activities (from none in 2009 to 7 in 2013); and level of external funding (from $730,000 in 2009 to $10,750,000 in 2013). On these measures, the group has attained a level found in neuroscience groups at many first-tier academic institutions.

ACCOMPLISHMENTS AND ADVANCEMENTS

Over the past 6 years the TN group has received consistently high marks from ARLTAB and has been repeatedly cited as a model for how a new group can effectively be developed at a government research laboratory.

Publication rates and journal quality have continued to rise to impressive levels and represent a very significant accomplishment. While further improvement in the quality of journal publication is urged, the TN group's productivity is on a par with what might be expected from recognized academic institutions working in the domain.

The TN group has successfully attracted higher levels of outside funding and now enjoys a level of external support that matches that of most first-tier academic institutional groups in neuroscience. This is an outstanding accomplishment.

The number of postdoctoral fellows in the program originating from first-tier academic institutions has grown considerably. Overall, the program now employs an impressive group of early-career scientists. The consistent investment in the growth of access to intellectual capital is exemplary.

In 2012, HRED completed the renovation of its Aberdeen headquarters. This renovation included the construction of the new MIND laboratory for the neuroscience group. Although somewhat smaller than would be ideal, this lab is an excellent state-of-the-art facility that is well built and well equipped. It is likely to prove to be an excellent facility for the group in the years to come.

Brain–Computer Interaction Technologies

While ARL's program in brain–computer interaction (BCI) technologies is only a few years old, it has made significant strides in fundamental research and in the development of applications. ARL has carved out an appropriate niche in the BCI community and is well-positioned with a clear emphasis on enabling practical BCI systems for soldier support. The decision to explore the integration of other sensing modalities—for example, electrocardiography (ECG), electromyography (EMG), galvanic skin response (GSR), and eye movements—into EEG-based BCI applications is conceptually strong and innovative. Overall, BCI has the potential to lead theoretical and practical breakthroughs in achieving maximum application performance with minimum invasiveness.

The applications and demonstrations shown indicated clear evidence of innovative fundamental and systems-based research. In particular, the integration of rapid serial visual presentation (RSVP) with the RAVEN system (RSVP-based adaptive virtual environment with neural processing) represents a significant fundamental advance. The cross-validation of performance estimates from two tasks (driving and RSVP) is a significant achievement, showing the generalizability of the work across multiple BCI applications. The use of transfer learning to train EEG classifiers using data from previous subjects is innovative and appropriate and has the potential to significantly reduce individual-specific training time needed for BCI systems. The use of sliding windows in hierarchical discriminant component analysis (HDCA) to deal with temporal variability in BCI responses is well-considered and solves a significant practical problem in the performance of these systems.

Real-World Neuroimaging

The real-world neuroscience group outlined a project to develop novel EEG measurement technologies coupled with the development of supporting algorithms. The project goal is to design systems for specific tasks rather than a single system that can work in all contexts. Some substantive directions of the work were described, among them to overcome real-world limitations for use of the electrode system so that it (1) works with hair, (2) slips on and off easily without significant setup, and (3) has high enough sensitivity to capture the signals necessary for the specific task. Overall, project goals and potential applications were clearly articulated and progress to date was illustrated by demonstrations.

Brain Structure–Function Couplings

Finite-Element Head Model

The Finite-Element Head Model project involves a rigorous method for incorporating anisotropic properties of biological tissue into a finite-element model for use in the development of head protective systems. This is an important goal for which the neuroscience group appears to be well qualified. The group evaluated this model using real brain pressure datasets from a cadaver study conducted several years ago. The results demonstrated that the model was considerably more accurate than had been expected. A suggested future direction would be to model the diffusion tensor imaging (DTI) abnormalities from the postmortem brains of individuals with blast or concussive injuries. The effects of an intact, living vascular system, cerebrospinal fluid channels, and interstitial pressure gradients might yield a very different outcome than is seen in impact-damaged cadavers.

Functional Connectivity Project

The TN group appears to have made significant headway in assessing several tools for causal modeling in EEG data. These are state-of-the-art tools that have not been well tested or validated for EEG use anywhere else, and the TN group is doing a solid job of identifying the strengths and limitations of these approaches. Given the central role EEG plays in HRED's translational portfolio, undertaking this validation is an excellent use of resources. The approach is sound, and the tools seem to be undergoing reasonable validation.

Phase Synchronization Tools in Electroencephalography

The TN group has made good progress in assessing tools for measuring and identifying phase synchronization in EEG data. These are tools that have not been well tested or validated anywhere else. Given the central role EEG plays in the TN portfolio, this project reflects an excellent use of resources. The approach is sound, limitations of the tools seem to be well identified by the research, and methods for maximizing EEG signal in a fieldable device are clearly being developed.

Decision Making in the Field Project

Using advanced psychological models of decision making in a simulated checkpoint screening task, the TN group is assessing the degree to which mission or task biases can be adjusted by instruction and incentives. The work is of very high quality and clearly Army-relevant. It will likely provide important data about how soldiers and officers take mission instructions into consideration and how effectively they can adapt their behavior to the needs at hand, and it might even offer insight into training effectiveness. In the future, the project needs to be expanded to disentangle expertise effects from task difficulty effects, and it also needs to allow for assessing the difference between soldiers and civilians in these kinds of tasks.

OPPORTUNITIES AND CHALLENGES

In the case of the TN program, many of the challenges represent opportunities to do more of what the group is already doing.

Brain–Computer Interaction Technologies

BCI technology based on neural recordings has emerged over the past 15 years as an important subfield of both translational neuroscience and bioengineering. This is evidenced by the dramatic increase in the number of publications and presentations related to BCI techniques in neuroscience journals and conferences.

ARL's mission focus on healthy soldiers poses an interesting challenge for BCI research, since the common goal of most BCI research is to treat or assist patients with sensory, motor, or cognitive disabilities. Hence, instead of using BCI technology for control as most clinically relevant BCIs do, the TN group has focused its efforts on the detection of mental states such as fatigue (state-based BCIs) or of external events such as relevant targets in a visual scene (event-based BCIs). Because their goal is to assist healthy soldiers in the field, the ARL researchers have resorted to the only currently viable noninvasive technology, namely, EEG electrodes placed on the scalp.

The BCI program is largely predicated on the assumption that computers and humans have complementary strengths (e.g., processing throughput versus higher-level reasoning and reliability and objectivity versus flexibility and situational awareness) and that hybrid systems leveraging BCI have the potential to achieve performance levels that neither a computer nor a human could achieve individually. This is a compelling notion, but it is not fully clear how the ongoing efforts and future plans specifically leverage, demonstrate, and validate it. There is the opportunity to do so, for example, by comparing the RAVEN system performance using RSVP-based BCI against state-of-the-art machine vision and automatic target recognition (ATR) algorithms. Such a comparison would show that the flexibility and situational awareness of humans greatly contribute to a computer system's ability to detect and recognize targets and other items of interest.

While the performance estimate cross-validation work is technically impressive, it is important to note that these systems are effectively detecting performance (often with significant delay) rather than predicting it in a temporal context. This may not be inherently problematic, given that some applications may benefit from BCI-based performance detection if performance assessment is not possible through other means. The group's claims to have the ability to predict poor performance before it begins to set in (e.g., early detection of fatigue that may lead to poor performance) need to be tempered. In point of fact, the current BCI system cannot determine if the brain is in a state that leads to poor performance or if the brain is just reacting to the poor performance (but see Baldassarre et al., 2012).[1] The goal of this research is ambitious and laudable and will necessitate a deeper understanding of the brain response and/or a demonstration of true temporal performance prediction.

Given that the BCI technology program is still in its infancy, the advancements in individual projects are impressive. However, the emphasis of the presentations on such projects made it difficult to appreciate the long-term vision of the program and the nested fundamental research questions and application goals that will be addressed as the program matures.

Reliability has become an important concern in the BCI field as is evidenced by DARPA's program in reliable neural interfaces. For BCI systems to become widely used in clinical and nonclinical applications, it is crucial that electrodes continue to record stable signals from relevant brain areas for at least months and ideally for many years. This is a particularly serious problem for invasive electrodes where foreign body reactions and the intracranial environment can affect signal quality and stability. For noninvasive EEG electrodes, the exact electrode placement can vary slightly every time the EEG cap is removed and reattached. The TN group needs to investigate whether its EEG-based BCI systems that have been calibrated for a particular subject can continue to detect relevant states and events over weeks to months without resorting to recalibration of the decoding algorithm.

It is widely assumed that field potentials recorded from different EEG electrodes provide partially redundant information. Redundancy is important because it can buffer these BCI systems from catastrophic failure and allow for graceful degradation. On the other hand, redundancy may allow BCI systems to transmit data from a smaller number of electrodes, thereby reducing the bandwidth requirements, which may be particularly relevant for wireless transmission. The ARL needs to explore the degree of redundancy of its systems by examining state- and event-detection performance as a function of the number of electrodes used, much as researchers who use invasive electrodes perform "neuron-dropping" analyses.

On a related note, it would be useful to explore the spatial organization of information content

[1] A. Baldassarre, Christopher M. Lewis, Giorgia Committeri, Abraham Z. Snyder, Gian Luca Romani, and Maurizio Corbetta, 2012, Individual variability in functional connectivity predicts performance of a perceptual task. *PNAS* 109 (9): 3516-3521.

across the scalp. Are there certain cortical regions that provide more accurate detection information than others? Is the information distributed evenly across the scalp? For example, there is evidence from single-cell recordings in nonhuman primates that neurons in the inferior temporal (IT) cortex modulate their firing rates to targets that are to be searched for in a complex scene in a visual search paradigm. Responses are enhanced in IT neurons that "prefer" the target, whereas responses are suppressed in neurons that do not prefer the target. Do EEG electrodes located over the temporal lobe provide better target detection capabilities than electrodes over the occipital, parietal, or frontal lobes? This suggestion to exploit the redundancy of multielectrode signals can be viewed as an alternative to source location, discussed above.

The applications of BCI systems that were presented were limited to state- and target-detection requiring no more than 1 bit of information. It might be useful to explore opportunities to extract richer information content than can be available with EEG alone or together with other biosensor technologies. For example, would it be possible to detect multiple levels of fatigue, attention, and arousal? Could EEG systems be used to detect states associated with subjects' ability to acquire information or to learn? Could the RSVP target detection system be expanded to detect more than one target class? For example, an operator may be looking for two different types of aggressors in a visual scene and respond differently to each.

Although their target detection system based on Rapid Serial Visual Presentation (RSVP) is quite impressive, it will be important to validate it against several control conditions to ensure that the improvement in search speed is attributable to target detection from the EEG system. One control condition would be to compare search speed using randomly sorted images that are not sorted via the EEG system. Another control condition would be to compare search speed using different machine vision and automatic target recognition algorithms to perform the sorting of images with potential targets instead of the EEG system. Such comparisons would help validate the larger claim that hybrid human–computer systems, leveraging their complementary strengths, can perform better than either system alone.

Real-World Neuroimaging

The TN effort to develop nonproprietary dry electrodes is a very challenging area wherein a breakthrough could significantly impact medical EEG, human factors, neuroeconomics, and neuromarketing and likely to lead to important new applications. The integration of electrode technologies with thoughtful statistical analyses for the purpose of artifact detection and classification could bring important and valuable contributions.

The TN group has designed a very sensible balance of projects in the portfolio and has organized a strong international collaboration to help achieve the group's goals. Among these goals are the following:

- *Phantom head development.* The work in support of the EEG phantom presents a good opportunity to perform standardized testing. The goal of having a real- world system requires the group to do viable real-world testing that extends to different levels of sweating and motion.
- *High-risk dry-electrode project*. Given the focus on dry-electrode pads as a key impediment, it would be useful to conduct analyses of the computational and energy requirements for a real-world system. For example, how much energy, processing power, communications capability, and data storage will be required? Furthermore, will new algorithms be required to handle the additional challenges of the real-world environment?

The current-generation dry-electrode system is in an early stage of development. The published time series from the electrode that was initially provided did not include measurements of brain waves. Fortunately, the panel was updated with sample brain wave recordings collected in real time. These indicated that while the overall stability of this dry electrode is impressive, the signals are very small.

They detect large artifacts, and it is not evident that cortical potentials are being picked up.

The TN group needs to compare the scalp measurements of these electrodes with other active dry EEG electrode systems (e.g., Gtec medical engineering) to ascertain the advantages and disadvantages of different approaches. Should there be significant differences in the scalp data, say in the signal-to-noise of averaged event-related potentials measured using the different dry electrodes and wet electrodes, the group might further make measurements of impedances and signals, humidity and perspiration testing (i.e., salt bridges), electromagnetic interference, and a standard 10-20 system for comparison of topography with the wet system to check for antenna effects from high-impedance electrodes.

The group needs to continue to consider alternative electrode types and analysis and signal enhancement methods that can reduce artifacts from electrode movement. Measures for evaluating signal quality need to be developed, and the TN group needs to ensure it is aware of and understands the lessons learned from prior work in this area.

Relevance to Protection from Traumatic Brain Injury

While the ARL is focused on the performance and protection of healthy individuals and it has noted that medical conditions are outside its mission, the problems that the group does focus on are relevant to performance and life-threatening situations that are commonly encountered by Army personnel and that are poorly understood. For example, a major threat to the performance of military personnel, during peacetime as well as wartime, is traumatic brain injury (TBI), particularly mild traumatic brain injury. Reports of soldiers recently returned from combat in Iraq found that 22.8 percent had sustained a TBI and that most of these were mild. The TN group has the potential to model and predict which areas of the brain are most susceptible to various mild TBIs and can in turn use these data to help guide the design of protective gear to militate against these injuries.

Obviously the work by TN could be of significant value with respect to identifying areas of TBI. For example, moving this work beyond impacts that might result from a blunt object striking a forehead could lead to techniques for identifying areas of brain damage when the injury is not detectable by routine imaging.

OVERALL TECHNICAL QUALITY OF THE WORK

Overall, the quality of the research presented, the capabilities of the leadership, the knowledge and abilities of the investigators, their scientific productivity, and proposed future directions are impressive. The work is well aligned with the clear and substantive mission to move neuroscience from the laboratory to real-world military settings—that is, from the bench to the battlefield. The TN group conducts high-quality neuroscience research that is routinely validated by its publication in recognized, peer-reviewed journals and is on a par with work at a good university neuroscience department.

The group leadership is highly effective and qualified, and there is a palpable energy and enthusiasm in the strong mix of early-career and mid-career scientists. The facilities are, for the most part, state of the art, and the group demonstrated impressive leverage and collaboration with the broader scientific communities at universities, industry, and other government laboratories.

5

Information Sciences: Autonomous Systems

INTRODUCTION

The Panel on Information Sciences at the Army Research Laboratory conducted its review of ARL's Autonomous Systems program on August 13-15, 2013. This chapter provides an evaluation of that work, recognizing that it represents only a portion of ARL's information sciences core technology competency portfolio.

While there was considerable variation in both the quality and impact of the research presented, the researchers were largely aware of the progress in their fields, and that had a noticeable impact on their own work. ARL has recently recruited a number of very promising early-career scientists. Careful attention needs to be directed at ensuring that they receive appropriate mentorship and career development opportunities as they develop their individual research portfolios. The new indoor Military Operations on Urban Terrain (MOUT) facility was impressive and will go a long way in furthering the goals of the intelligence and planning program. The tour of the ARL Sensors and Electron Devices Directorate's Specialty Electronic Materials and Sensors Cleanroom Research facility helped the review team understand the infrastructure support available to ARL researchers.

A summary assessment of research in each of four subject areas—manipulation and mobility, perception, robotic intelligence, and human–robot interaction—is presented in the following sections of this chapter. ARL has a leading program in the area of small-scale robotics. A demonstrated ability to design, fabricate, and test these devices gives it a place of distinction in this field. Similarly, research in the area of perception is being performed at a high level. With a mission to develop machine understanding of objects, actions, and interrelationships in a specified environment, this work is critical for advancing the state of autonomous systems. Ongoing research is focused on advancing unsupervised approaches to human detection and advancing sensing and perception capabilities on constrained platforms. Research in the areas of human–robot interaction and intelligence is addressing important problems of mapping, cognition, and communication, as well as issues related to trust in autonomous systems. This research is cutting edge and comparable to work at federal, university and/or industrial laboratories here and abroad, and portions of the work are poised for successful transition to applied research.

ACCOMPLISHMENT AND ADVANCEMENTS

All elements of the autonomous systems research program at ARL have continued to show progress, both in the quality of work and dissemination of results in high-quality publications. The program focuses on mobility and manipulation of robotic devices and on technologies that improve the usefulness of these devices, such as intelligence, perception, and improved human–robot interaction. The ARL research program is part of a larger collaborative effort involving external partners. A better definition of the role of the internal research in the overall program goals and continued collaboration with partners is strongly encouraged.

Research in the area of manipulation and mobility is closely linked to the ARL's Collaborative

Technology Alliances (CTAs) in Autonomous Systems,[1] where significant collaboration with those partners is to be found. Three areas were highlighted during the review: replicating locomotion found in biological systems to improve robot mobility, autonomous manipulation of robots, and piezomicroelectromechanical systems (piezoMEMS) technologies to develop small-scale robotic systems. New updates on the project related to the CANID robot,[2] mimicking the movements of a canine hound, were presented. The primary thrust of the new development was the addition of a flexible spine to the robot. This is a challenging and interesting project, and the addition of this key degree of freedom to a walking robot is a good idea, because it more closely resembles the complexity found in nature. There needs to be a concerted effort to better understand the physics of this machine. Researchers have proposed low-order models for the system, and it might be fruitful to continue this line of inquiry. Good modeling will be imperative in any numerical simulations required to explore gains that are possible and to guide the focus of new experimentation.

Work related to self-righting robots is of a very high caliber and also has direct applications in the field. This was evident from the fact that the project was conceived through interactions with soldiers who are often confronted with the task of retrieving immobilized robots in combat. The research seeks to develop solutions for a broad class of physical conditions that affect stability of mobile robotic platforms. The current focus is on examining the underlying mechanical issues of self-righting in a quasi-static environment. It was not clear how the upright, stable position would be sensed on a sloping surface, where self-righting is most likely needed. ARL's intention to move toward a consideration of dynamics in 2014 is applauded.

The piezoMEMS research and associated small robotics effort, in the Board's judgment, is first rate, with elements that are at the vanguard of this field. The robotic devices under development with integrated piezoelectric materials demonstrated work that is at the forefront of MEMS design, fabrication, and experimentation. Specifically, the work in motion generation at the MEMS scale is seminal. Large-amplitude motions are being created at the micron scale using integrated actuators, structures, and electronics, co-fabricated on silicon. Techniques and approaches to generating articulating limbs with integrated flexure hinges and actuators represent advances in the engineering of MEMS technology. This has broad implications and applications to numerous MEMS systems—for example, MEMS-based microscale sensors and instrumentations such as mass spectrometers on a chip, drug delivery systems, and chemical assay analysis, where controlling microfluids are of fundamental importance. The work being performed by ARL in the piezoelectric actuation of MEMS will impact more than just the creation of bioinspired microscale robotic systems.

The research projects in perception are of a high caliber. The work focuses on developing techniques that allow for developing a description of the robot's environments from sensor data. While there has been considerable progress toward describing environment for the purpose of mobility, deriving higher-level descriptions such as subtle cues and references that distinguish different behaviors and intents, recognition of specific classes of objects and features that are directly relevant to tactical behaviors, and labeling of object, features, and terrain classes remain a challenge.

The current research plan is focused on three critical areas: perception on constrained platforms, robotic intelligence, and human–robot interaction. Within the area of sensing and perception on constrained platforms, the scale and size of platforms being explored in the autonomous systems enterprise pose technical challenges in sensor design. Sensors have to deliver the requisite accuracy and precision for surveillance and navigation, but they also have to reconcile with power limitations on smaller platforms. Other problems being addressed in the perception area include human detection in still images and strengthening object and material recognition capabilities, including an ability to recognize actions and imminent actions. The latter is based on scene parsing and action grammar and represents an

[1] There are currently two active CTAs related to autonomous systems: Micro Autonomous Systems and Technology (MAST) and Robotics.

[2] CANID is a quadruped designed to test hypotheses regarding dynamic bounding using an actuated compliant spine mechanism.

interesting approach. The problem of developing real-time human detection algorithms is important, because existing approaches are based on supervised learning techniques that are computationally cumbersome. In operational environments that may be diverse and exhibit large variations, computational efficiency is an important consideration. The unsupervised learning approach used in this work is clearly more efficient but may still yield false positives, and additional work is required to overcome this drawback. The basic approach for each of the research tasks is fundamentally sound, breaking new ground. Results of this research are publishable in archival literature, and the work is at par with research being done at universities and other laboratories. The researchers are aware of related work being done elsewhere and recognize deficiencies in their individual approaches. Each presented a good plan for the future activities.

The primary accomplishments in robotic intelligence are advances in mapping capability, control for communications, and cognition. Much of this work is being published in top journal and conference venues (including the *International Conference on Robotics and Automation*, the *Institute of Electrical and Electronics Engineers Proceedings*, and the *International Journal of Robotics Research*), which attests to the overall quality of the research. Former students funded by the CTAs have been recruited to ARL and are important contributors to the research effort. Some of the 6.1 (basic) research projects are also making their way to 6.2 (applied research) applications, an important step for transitioning this work to the field.

In the area of long-duration three-dimensional (3D) mapping and navigation, the principal focus is on the development of a laser-based approach to 3D mapping that combines features from three existing mapping techniques. Demonstrating the effectiveness of the approach by deploying it on physical robots is an important accomplishment. Another thrust of intelligence research is on developing robust methods for control of mobility and communications. The primary focus of this effort is the development of a centralized, optimal solution of mobile node positions, subject to point-to-point communications constraints. While promising results were presented, additional details are necessary, particularly for issues such as scalability and whether such issues impose limitations on the proposed approach. Research in intelligence is also examining new cognitive architectures for robotic control. This work is focused on developing a new cognitive architecture that combines long-term memory, working memory, and perception. The mapping problem is driving this development, but it is difficult to understand how the cognitive approach improves mapping performance.

In the area of human–robot interaction (HRI), research at ARL is looking at design issues for safe operation of autonomous reconnaissance systems in complex environments. The emphasis of this effort is human factors experiments to investigate interaction with, and control of, multiple autonomous systems. The design of interfaces is an important aspect of this investigation. Studies are focused on graphical user interfaces (GUIs), multimodal interfaces (including voice), and telepresence with stereovision and haptic interfaces. The experimentation conducted at Fort Benning has yielded an important basis for making design decisions. For example, experiments have demonstrated voice commands to be suitable for discrete actions but less so for controlling continuous processes. Similarly, the research has demonstrated how audio cues in 3D improve situation awareness in telepresence tasks.

The RoboLeader project continues to be an important component of the ARL HRI program. The research draws on a large body of experimental work related to evaluating the effectiveness of autonomous and semiautonomous control of teams of robots. The RoboLeader intelligent system was evaluated in this context and shown to provide benefits from the standpoint of both task performance and workload management. Testing with humans showed individual differences in performance: People with high spatial ability and significant videogame experience had better situation awareness of the mission environment. The results have implications for personnel selection, training, and user interface design.

Another research thrust in the HRI arena is bringing greater understanding of automation actions to the human in the loop. The focus of this effort is the use of visual display screen overlays to communicate robot perceptions and intentions to a human operator during an automated navigation task. The experimental approach is sound and based on prior studies of shared mental models and automation transparency. Results of this work support the use of such visual aids as an approach to reduce teleoperation occurrences, teleoperation times, and subjective workload.

The HRI group's publications reflect a broad understanding of the science and research conducted elsewhere—related work is cited and contributions are placed in context. The group has also edited a book, *Human-Robot Interactions in Future Military Operation*,[3] which includes input from external sources, including academia. It also has a demonstrated record of successfully transitioning its work to the U.S. Army Tank Automotive Research Development and Engineering Center (TARDEC) robotics programs.

OPPORTUNITIES AND CHALLENGES

It was not clear how the individual research projects in each area—manipulation and mobility, perception, robotic intelligence, and human–robot interaction—of the ARL autonomous systems enterprise fit within the larger research effort. Without such a road map, there is very little indication of the connectivity of the research projects, both within the subareas and across the enterprise.

At a fundamental level, ARL can take additional steps to enhance the quality and impact of its research efforts. There is a trinity in research and development: analysis, computation or simulation, and testing. Analysis is essential, and there is room for improvement on this front, before one proceeds with numerical simulation or building and testing artifacts. Results from analytical modeling can guide the subsequent steps in development and identify possible missteps: This analytical component needs to be integrated into the approach to research. For example, it is not enough to build a robot and begin to generate a gait similar to that of an animal—one must understand the physics behind the energy converted in a machine when using such a method of locomotion.

In the area of manipulation and mobility, there is need for a more coherent approach to vehicle design and development. It would appear that while many excellent issues are being addressed, the overall approach is somewhat ad hoc. For instance, there is an absence of nondimensional scaling in platform design. Characterization of the fundamental physics of flying vehicles—length-to-diameter (L/D) ratio, drag polar, coefficients of lift and drag, and power requirements—must be part of the basic design philosophy. Similarly, metrics for system performance evaluation in generalized terms, such as actuation efficiency, propulsive efficiency, hover power loading, power to weight ratio for the actuator, endurance, and specific energy of the fuel source, would add focus to coupled systems and vehicles to include physics-based performance attributes. For robot systems, the specific resistance or cost of transport for any locomotive machine, natural or man-made, is a measure of a machine's locomotive efficiency. It would be beneficial for ARL to encourage this traditional thinking as part of the research mindset.

There is an opportunity to perform simulations of robots and vehicles based on analytical models of the physical systems operating in different environments and to include uncertainties in these models. The models can further be coupled to real control systems, leading to hardware-in-the-loop control design. The ARL may need to consider procuring development hardware, such as D-Space, for robotic controller development. Such systems would accelerate results and allow the integration of complex, nonlinear controllers, based on traditional sensors and sensor fusion, states of the machine, learned behaviors, and complex logic of state machines. Once developed, successful controllers could be programmed, at which point the developmental kinks have be sorted out, to perform laboratory and field tests of the new controllers.

Integration of systems components is essential to the robotics research area. The system is much more than the sum of its components—nonlinear interactions, sometimes stochastic in nature, can have significant impact on overall operation. In this context, an integrated approach (systems engineering) is a fundamental (6.1 level) domain of research. Such an approach will also allow researchers to best trade

[3] Michael Barnes and Florian Jentsch, eds., 2010, *Human-Robot Interactions in Future Military Operations*, Ashgate Publishing Company, Burlington, Vt.

concept options against the desired output or value functions. There is an opportunity for the ARL autonomous systems enterprise to assume the leadership in advancing a highly quantitative and scientific approach to systems engineering as it relates to integration of systems components into the robotics research area.

Other general suggestions related to this area of effort may be summarized as follows:

- Notionally establish a family of small robots (ground and air) of varying size (between 1.0 g and 100 kg) and define and reach both the baseline and performance goals for each robotic class. These specifications could be based on a limited selection of potential Army scenarios or vignettes.
- Establish a directed robotic mobility propulsion effort to unify and direct activities required to produce very high power and high energy density systems.
- Establish an integrated design and optimization methodology (considering key parameters like energy, power conversion efficiency, and locomotive efficiency) for the design of these highly integrated robotic systems. The interdependence of all the subsystems will quickly become clear to the researchers as they try to categorize future robotic systems.
- Consider the establishment of a robotic mobility systems integration laboratory. This laboratory would allow for the integration of complete physics-based air and ground mechanics models of selective robots with candidate control systems in a simulated real-world operating environment.

Although the mission statement pertaining to perception research is rather broad, the actual ongoing focus is restricted to a rather narrow set of problems. It was not clear if this focus was driven by gaps or deficiencies identified by the Army or how this work fits with contributions from partners. As an example, perception needs to support more than obstacle avoidance; it needs to support a richer semantic understanding of terrain that would be useful for people as well as autonomous vehicles. Furthermore, there is a need to address scalability issues with regard to sensor capabilities, such as varying fidelity and power requirements with size. Sensors provide measurements of data pertinent to the operational environment. For autonomous behavior, however, it is necessary to process these physical measurements to glean information. In the area of unsupervised human detection, researchers need to explore a hybrid supervised/unsupervised algorithm that would not only be computationally efficient but could also curtail the number of false positives that the current approach seems to yield.

Sensors are also linked to communications. The processing and communications power available to a single platform determines what is transmitted—measurements, processed data, or commands. The work on parsing and action grammars could benefit from transmitting unknown constructed images over a communication network to a node with greater processing capability and reference data. In this context, focus needs to be directed at combining scene parsing, scene surface layout analysis, and 3D reconstruction to advance the state of the art in overall scene understanding.

It may be useful to place bounds on the problem dictated by mission requirements. This would help identify quantitative metrics against which progress in research tasks can be measured. Ongoing research in perception is aimed at enabling cooperative interaction between robots and humans at multiple levels. Accomplishing this within a mission context, accepted military doctrine, and social norms of the society in which the soldier-robot teams operate is a major technical challenge.

Overall, the research programs in intelligence reflect a broad understanding of the underlying science and research conducted elsewhere. However, researchers need to more clearly state the scientific problems they are addressing and the metrics they are using for evaluation. The work also needs to be properly placed within the current state of the art. Presenters need to better articulate the primary contributions of the research and how the presented approaches achieve those contributions. The recently hired Ph.D. researchers need to better clarify how their new work at ARL is going beyond their dissertation contributions as students.

More broadly, the challenges of robot intelligence specific to the needs of the Army need to be clarified. While the three areas related to mapping, control for communication, and cognition are important, they do not provide a perspective of the ARL vision for robotic intelligence for Army applications.

In the work on long-duration 3D mapping and navigation, there is a need for justification of why the approach performs better for this problem of long-duration mapping, including identifying metrics against which progress can be gauged. The scalability issues with the approach were correctly identified, and it will be interesting to see how the proposed strategy of forgetting parts of the map helps address this problem. In the area of robust control of mobility and communications, it is important to calibrate the performance of the approach against related methodologies in the fields of mobile ad hoc networking and optimization. There could be some important linkages of this work to the network sciences CTA, and that could present opportunities for leveraging.

The design of new cognitive architectures for control can play an important role in robotics. However, it is difficult to understand the benefit of this cognitive approach to the mapping problem. Many working solutions for mapping exist that do not make use of cognitive solutions, and it is not clear how such an approach improves mapping performance. The approach could instead be motivated by a different application domain requiring more high-level cognition, such as a scenario that entails going to the back of a building and watching a door for persons of interest.

In the area of HRI interface design, the breadth of experiments is clearly commendable. The experiments, however, are conducted as separate efforts and employ different tasks. This limits the ability to draw meaningful insights from the results. For example, an Android touchscreen interface was compared to an Xbox controller, and separately a speech interface was compared to manual navigation through a GUI. An opportunity exists to place these experiments and results within a larger context and to interpret results across experiments to provide more general design guidance.

In HRI research efforts related to understanding automated system actions, the initial experiments provide encouraging results for simple task scenarios involving few factors at a time. There is a need for follow-on experiments that validate the use of visual aids when performing more complex tasks, particularly in a multitasking environment, and on dismounted soldier interfaces.

It is important to conduct more basic research that takes advantage of ARL's unique access to soldiers. As all of the services move toward the inclusion of more robot systems, it is necessary to conduct the basic research that will allow these systems to be effective and efficient members of the team. It was heartening to note the existing collaborations with researchers in cognitive architectures and perception. This model needs to be replicated across other projects at the 6.1 level, where HRI can help guide the development of capabilities that are still very difficult to achieve without a human in the loop (e.g., perception work). Even with increased system capabilities, both in terms of intelligence and perception, there will still be a need for a soldier to interact with the robot systems. The nature of the HRI will change, from remote operation to a supervisory role, and eventually to interaction with the robot as a team member. HRI, however, will remain the key to the effective deployment of robots in the Army and other services.

The HRI group would benefit greatly from wider exposure. ARL could consider sponsoring a workshop that would discuss HRI from the soldier's perspective. In addition to inviting academics and people from the other service laboratories, sponsors of HRI research from other agencies such as the Office of Naval Research, National Science Foundation, Army Research Office, and Defense Advanced Research Projects Agency could bring valuable insight to this effort.

On a more general level, much of the work presented was mature; new opportunities for providing input and feedback on projects that were in their inception stage could be beneficial to the overall research enterprise.

OVERALL TECHNICAL QUALITY OF THE WORK

Many of the ARL internal research projects in the autonomous systems enterprise are of very high quality and have benefited from engagement with other research institutions, including partners in the CTAs. For each of the key areas—perception, intelligence and planning, human–robot interaction, and manipulation and mobility—the overall technical quality of the work is high and is being recognized as such by virtue of publication in archival journals and proceedings of recognized conferences and symposia. Also, the recent *Research@ARL* monograph series on autonomous systems[4] is commendable. For most of the work reviewed, the scientific quality is comparable to that available at other federal research laboratories and at universities here and abroad. The research staff is very well qualified to undertake the research projects and is broadly aware of the state of the art in the field and ongoing research at other institutions. A number of research scientists have been newly recruited, and they promise to contribute to an exciting future for the ARL. Mentorship for these early-career scientists will be of paramount importance for their long-term success at ARL. The laboratory facilities and the infrastructure are state of the art and supportive of the ongoing research activities.

The internal research efforts at ARL are being performed against the backdrop of a research roadmap that includes contributions from partners and contractors. It would be useful to clarify this context in order to better understand any gaps that might exist in the research approach. Other specific suggestions to improve the overall research enterprise include the following:

- Require researchers to clearly articulate the existing technical challenges in their research and how and why the proposed tools and methods are likely to resolve those challenges.
- Require all researchers to identify quantifiable metrics against which progress can be gauged. This would allow for setting meaningful goals and adopting a research agenda that targets nonincremental advances.
- As ARL continues to build its research staff, give some attention to bringing in midcareer and senior personnel to mentor the outstanding early-career scientists who have been recruited.
- Look for additional ways to increase interaction of its researchers with leaders in industry and academia, given that limitations on travel have restricted this important function.
- Focus on developing a mature framework to guide the conception, design, development, and testing of small, unmanned autonomous systems, including definitions of pertinent parameters and their domain (values).
- Adopt a systems integration approach as a fundamental research thrust. Existing projects would benefit significantly from such a research thrust.

[4] *Research@ARL: Autonomous Systems*. Available at http://www.arl.army.mil/www/pages/172/docs/Research@ARL_Autonomous_Systems_July_2013.pdf. Accessed September 20, 2013.

6

Materials Sciences: Biomaterials, Energy Materials and Devices, and Photonic Materials and Devices

INTRODUCTION

The Panel on Materials Science and Engineering at the Army Research Laboratory conducted its review at Adelphi, Maryland, on June 11-13, 2013. This chapter provides an evaluation of that work, recognizing that it represents only a portion of ARL's materials sciences core technology competency portfolio. The review addressed the areas of biomaterials, energy materials and devices, and photonic materials and devices.

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, according to the ARL. Materials research efforts and expertise are spread throughout the ARL enterprise. As the ensemble of the materials discipline and capabilities, the area of materials 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.

The criteria for the assessment are the technical merits of the work; facilities and equipment; research talents; underlying broad-based sciences; and the desired impact and the balance of theory, computation, and experimentation. They include as well alternative directions or approaches to catapult a project toward its promised accomplishments.

In this chapter, ARLTAB's carries out its assessment by category of material and by project and goes on to offer general observations, propose future thrusts, and make suggestions.

Overall, the researchers and the management are of high caliber and deserve kudos. Researchers appeared ebullient and passionate about their work. ARL's work in preparing for the review was superb. The ARL Director's webinar overview and the read-ahead materials, presentation viewgraphs, poster materials, and laboratory tours greatly facilitated the review process. It was highly valuable to have an interactive session with the ARL Director to become acquainted firsthand with the ARL's mission and goals. This is also the first review involving the new director of ARL's Sensors and Electron Devices Directorate, whose vision and plans were presented in an energizing fashion.

As for institutional aspiration, there is no shortage of challenges and opportunities. One of the larger questions being asked is, How can ARL be meritoriously unique as a research laboratory that is nourished by an innovative culture? In expanding innovation, discovering new science and new technology is as rewarding as crafting new uses of existing technologies to develop advanced Army products.

Striking a balance between the projects that tackle known unknowns, driven by application and innovation on demand, and the projects that explore unknown unknowns to achieve high-risk and high-reward outcomes needs to be an ongoing effort.

Another opportunity is presented by asking how the distance between the science and the Army end-use applications can be narrowed. The ARL scientists maintain knowledge of Army applications through direct exposure with the end-users in the field. To enhance human capital, nurturing a working environment that offers positive energy, organizational stability, and high retention rate is essential. Establishing a comprehensive reward system is another challenge and opportunity. Several ideas that may be considered are awards (monetary and nonmonetary), internal recognition, external peer review, research freedom, laboratory-wide recognition of stature (e.g., fellowships), and dual-track career advancement.

All the projects reviewed are engaged in collaborative efforts to various degrees; this is commendable. The next level of excellence can be achieved by improving efficiency of collaboration to deliver better focus, quality, and selection of projects. Internal collaboration across the divisions and directorates is as beneficial as extramural collaboration.

In today's fast-moving technological landscape, additional opportunity is presented by the challenge of effectively utilizing commercial technologies, particularly as they pertain to wearability, mobility, and connectivity, which are critical to the well-being of the soldier. A systematic, structured effort to scout technologies from the private sector to complement in-house projects will be highly rewarding.

As technology marches on at an unprecedented pace, it is important that new approaches to shorten the research cycle from science to useful product always be on ARL's radar. A concerted effort to understand future needs and craft projects relevant to them is the ultimate challenge and opportunity. To this end, the materials genome initiative is one frontier that could usefully be paid attention to.

Branding and marketing represent an additional opportunity worthy of consideration so that good work is not kept secret. Measures of success for the research work—for example, invention disclosures and patents, citations, and publications—need to be tracked. When it comes to publications, value versus volume is another judgment to be made.

Most of projects presented are excellent and exerting pervasive impact. The scientific soundness and the use of the fundamental sciences are outstanding. It is commendable that the ARL materials science talent pool has a good mix, ranging from experienced, savvy scientists and engineers to the bright, early-career professionals. There appears to be good diversity with respect to gender and ethnic groups. The project portfolio fits well with both global thrusts and the national agenda, with research projects falling at the intersection of the pillar technologies of biotechnology, nanotechnology, advanced materials, energy, and the environment.

To further enhance the research output, project feasibility and milestones call for critical periodic evaluation. Some of the projects in the portfolio are particularly impressive.

The biomaterials group is making particularly noteworthy progress, following the ARLTAB's previous suggestions to recruit a new branch chief and to begin to establish a long-term program in biotechnology. The project on synthetic biomolecular materials is especially significant for the Army. It addresses needs in situation awareness and force protection in such areas as on-demand production of biomolecular sensing materials in response to new and emerging hazardous threat materials; functional biomolecular materials that are stable in austere environments; persistent surveillance; and ubiquitous sensing. The project has already shown success by developing iterative and integrated multiscale computational biology capabilities—this is topnotch research. The project has also demonstrated, for the first time, rapid development of peptides as synthetic alternatives to antibody-based bioreceptors, which are difficult to produce and maintain in the field. The use of biogenerated fuel to drive a fuel cell and generate a periodic power boost is another research project important to the Army.

ARL is a technology-driven and warfighter-focused institution; developing technologies to deliver ubiquitous power and energy for warfighters is a compelling mission. The project on hydrogen production from water by photosystem for use as fuel in energy conversion devices offers promise. The project on nonnoble metal catalysts for alkaline fuel cells studies the catalysts supported on graphene. Impressive power density (300 $mWcm^{-2}$ at 60°C) was demonstrated using a Pt-free cathode with an anode of standard carbon-supported Pt. If the performance can be improved further and stability demonstrated, this could represent a significant breakthrough. For lightweight, quiet, efficient, and reliable power sources that would enhance soldier combat capability, the project on fuel cells for military applications tests and evaluates commercial technologies—namely, direct methanol fuel cells and solid oxide fuel cell (SOFC) systems. Fuel cells reduce weight and decrease the logistic burden associated with batteries. The 300 W SOFC systems, operated on propane, can be thermally cycled more than 40 times between room temperature and 800°C without significant degradation and can be heated to 800°C in less than 10 minutes. The system was successfully tested in an unmanned aerial vehicle. This represents an upward potential for Army applications.

In the area of photonic materials and devices, the accomplishments of the project on electromagnetic modeling of quantum well infrared photodetectors (QWIPs) are laudable. The model described explains the quantum efficiency (QE) of all existing detector structures, including the most advanced optical effects, and expresses the detector QE in terms of the material's absorption coefficient and the volumetric integral of vertical electric field. Because affordable, high-speed, high-resolution, long-wavelength infrared (IR) cameras are critically important to the Army's night vision, large-area surveillance, and navigation in degraded vision environments, the success of this project is of enormous value. As a leader in QWIP technology, ARL can leverage this achievement to develop advanced technology and to strategically brand ARL's leadership.

Another high-impact project is developing a low-cost, III-V, direct-bandgap long-wavelength infrared (LWIR) detector for night vision technology. LWIR detection is a niche Army technology requiring dedicated equipment and highly specialized skills and tool sets. The research involves the growth of defect-free unstrained and unrelaxed InAsSb material on binary substrates such as GaSb, InSb, or InA. This detector is expected to be a disruptive technology for the LWIR field and to potentially replace the costly II-VI based technologies.

As for laboratory physical facilities, state-of-the-art equipment and instruments are available to perform quality research work, and there are many material characterization capabilities—for example, ultrafast THz and nano-nuclear magnetic resonance (nano-NMR), time-resolved ultraviolet (UV) materials growth and characterization, and a clean room fuel-cell laboratory, which are all supported by trained and knowledgeable personnel. However, synergistic capabilities can be further harvested through the tie-in of facilities across division branches, as well as through collaborations with the targeted external facilities.

The sections below summarize the comments and suggestions for three groups of projects: biomaterials, photonic materials and devices, and energy materials and devices.

ACCOMPLISHMENTS AND ADVANCEMENTS

Biomaterials

Synthetic Biomolecular Materials

The investigators have successfully demonstrated, for the first time, rapid development (in less than a week) of peptides as synthetic alternatives to antibody-based bioreceptors, which are difficult to produce and maintain in the field. This project, which used combinatorial chemistry and genetically modified *E. coli* to find peptides capable of strong binding to inorganic materials, is excellent research. For example, finding 15-unit amino acid sequences that bind strongly to metals and other targets compounds will facilitate development of biosensor technology. This research addresses an important need in situation awareness and force protection such as on-demand production of biomolecular sensing materials in response to new and emerging hazardous threat materials. The collaboration with the Institute for Collaborative Biotechnologies at the University of California at Santa Barbara seems to be productive; extended visits by staff members leading to joint publications are encouraged.

Tissue Scaffolding

This is an excellent effort and certainly is of benefit to the Army because it is aimed at designing nanofibrous scaffolds that enable wound healing and regeneration of damaged nerve tissues. These scaffolds will be used for three-dimensional (3D) cell culture platforms for the study of blast-induced traumatic brain injury (TBI) at the cellular level. The tissue engineering research involves a scaffold for neural cells, and the work shows the cells aligned if the fibers are oriented, a feature well known in the field. The work is being carried out expertly; the gradient approach to place adhesive protein in the scaffold deserves further study.

By far the most interesting application was that the scaffolds were used to culture neural cells, which could be exposed to a simulated blast or shock wave followed by analysis of changes in the metabolic characteristics of the cells. This research could lead to unique treatments to heal nerve injuries as well as to get a better fundamental understanding of neural damage from ballistic blast in order to design better protective equipment.

Synthetic Biology Using Quorum Sensing

Work on harnessing the natural bacterial communication system involving the communication molecules AI-2 is relevant to the Army needs in areas such as bioterrorism, warfare, food and water safety, medical applications, and fuel integrity. The investigators use synthetic biology to engineer a bacterial sensor and to rewire bacterial communication machinery in order to develop a robust and sensitive biosensing system. Additional theoretical studies in gene circuits would help to further develop advanced and/or improved systems for a wider range of applications.

Nanocellulose

Nanofibrils of cellulose (NC) is an area of research relevant to Army needs because it has the potential for developing materials that exhibit high strength and modulus (comparable to Kevlar), controllable adhesion and dispersion properties, and nanoscale-enabled transparency. This NC product could be an excellent logistical material that is sustainable, inexpensive, bioderived, biocompatible, and eco-friendly. Theoretical investigations (at ARL or in conjunction with outside academic collaborators) into the structure and physicochemical processes involved in the development of NC are encouraged. This work is interesting but does not seem to have breakthrough potential. The work on improving impact strength, the ability to reinforce polymer matrices to yield transparent composites, and the synthesis of bio-based polymers is of high quality, but it is not many steps beyond the current state of the art in composite technology. Also, the type of research involved in this project involves mainly chemistry and is only marginally biological (and thus not directly related to biotechnology).

Effects of Atmospheric Environmental Conditions on Bio-aerosol Properties

This project develops a system built and tested to measure the effects of atmospheric environmental conditions, including gases, sunlight, and humidity on the UV-laser-induced fluorescence spectra and viability of bio-aerosols. This project is clearly critical to developing useful tools for soldiers on the ground, who face serious environmental threats. However, it appears to be focused on large-scale measurement capabilities that were not distinguished from other efforts in environmental monitoring and to follow rather than lead efforts that address the need for monitoring highly mobile individual soldiers. The results to date are interesting and informative, and the fluorescence data are useful. It would be useful to consider adding other spectroscopic techniques, such as Raman scattering, to obtain complementary spectral information. Theoretical studies on the photochemical pathways and fate of the photoproducts would also help to provide a fundamental basis for the project. Atmospheric photochemistry is well known, and the study of simple bio-aerosols needs to be expanded to include the study of more complex systems. The project on bio-aerosol chemistry involved interesting, high-quality research, and it is important to tie it in with other work on modeling toxic plume development due to industrial accidents or to a bioterror event. Collaboration with scientists at other laboratories and universities is strongly encouraged.

Energy Materials and Devices

$Li_7La_3Zr_2O_{12}$ Electrolytes

Samples of high quality were fabricated by hot-pressing. They were evaluated in electrochemical cells by cycling. While the current passed at room temperature was modest (0.01 $mAcm^{-2}$), the cycling performance was stable. Some electrochemical impedance spectroscopy (EIS) was also presented. Future work is planned in evaluating electrode impedance. The refractory nature of the electrolyte is likely to facilitate the design and construction of Li batteries with a broad range of operating temperatures, similar to NaS batteries but with higher voltage and specific energy. Options also exist for further improving Li ion conductivity by doping with other ions.

Materials for Advanced Battery Chemistry

In collaboration with the University of Maryland at College Park, electrolytes were formulated for Li/S, Na, Mg, and conversion reaction materials.

In Situ Investigation into High-Capacity Alloy-Type Li-Ion Battery Anodes

The objective of this work was to systematically investigate by means of atomic force microscopy (AFM) the volume changes occurring during charge and discharge using samples of controlled geometry (size-controlled Si islands formed by microfabrication). The AFM was able to capture the morphological evolution of the islands during electrochemical cycling and showed that islands as small as 100 nm in height and diameter readily suffer irreversible mechanical degradation. It is not clear, however, how to avoid this type of degradation. Nevertheless, the approach used to systematically investigate degradation is good. Well-defined geometry is likely to allow the development of theoretical models describing state of charge and the associated volume changes.

Atomic Force Microscopy for In Situ Analysis of Li-Ion Battery Materials

The formation of a thin, contiguous solid electrolyte interface (SEI) layer is important for the satisfactory operation of Li-ion batteries. It is important that it be thin and be a reasonable Li-ion conductor but a poor electronic conductor. The layer is typically a few nanometers to ~100 nm thick. This layer is difficult to characterize. In the present work AFM was used to image the SEI layer. This appears to be a very fruitful way of investigating the dynamics of SEI layer formation. It would add considerable value if these studies are supplemented with electrochemical tests, such as EIS.

Oxidation Stability of Electrolytes from Density Function Theory Calculations

Stability is given in terms of voltage. Work shows that density function theory (DFT) can be used to identify the correct reaction mechanisms (and products). Calculations are in good agreement with the experimental results. This appears to be a very in-depth study. Two or three papers have been published to date.

Prototyping of 5 V Li-ion batteries

This work concerns the possible development of a high-voltage cathode for Li-ion batteries. $LiFePO_4$, $LiCoPO_4$, $LiMnPO_4$, and $LiNiPO_4$ were investigated using first-principles calculations. Through these calculations, $LiFePO_4$ and $LiCoPO_4$ were identified as good candidates. From the standpoint of thermodynamics, $LiCoPO_4$ is determined to be the best (highest voltage), while $LiFePO_4$ is shown to be more stable. The present work showed that a cathode containing both Co and Fe exhibited high voltage and was also stable. It appears that by suitably tailoring composition, it may be possible to achieve both good performance and good stability.

Liquid Electrolyte Li-S Battery

This is a good problem-solving project based on classic electrochemical methods to reveal qualitative mechanisms during discharge. Awareness of the effect of these materials on the entire system is an important strength of this work. There are several recent publications in high-quality technical journals.

Developing Next-Generation Thermal Batteries

The approach of this project consists of forming multilayer laminates of two metals, Ni and Al. The individual layers are a few tens to a few hundreds of nanometers thick. The relative thicknesses are selected based on the final intermetallic composition desired, which in turn is based on the heat released during the thermite reaction. Very thin layers allow attainment of very high velocities of reaction front travel (10 ms^{-1}). Ignition is achieved at one end. This is a very specialized topic but of direct relevance to Army operations.

Nonnoble Metal Catalysts for Alkaline Fuel Cells

These catalysts are supported on graphene. By suitable thermal treatment, the catalyst is pyrolyzed to change its chemistry. Impressive power density (300 $mWcm^{-2}$ at 60°C) was demonstrated using a Pt-free cathode. The anode was standard carbon-supported Pt. The work is very impressive. If the performance can be improved further and stability can be demonstrated, this could represent a significant breakthrough.

Fuel Cells for Military Applications

The 300 W SOFC system operated on propane and could be thermally cycled more than 40 times between room temperature and 800°C without significant degradation. The system could be heated to 800°C in less than 10 minutes. Also, the system was successfully tested in an unmanned aerial vehicle. This represents a significant achievement for the SOFC systems and utility for military applications.

Palladium Membranes for Purification of Reformer Gases

Thin (500 nm) Pd membranes were fabricated by supporting them on lithographically patterned 15 μ thick Ni substrate having 15 μ hexagonal holes. A pressure differential of 20 psi could be maintained without rupturing the membrane. The permeation rates were comparable to or better than rates for other Pd membranes supported on other substrates (alumina, stainless steel). The reformate contained CO and H_2S as contaminants. The results are impressive. It is probably possible to use porous Ni foils (made by consolidating Ni powder). This may decrease the cost and may also improve strength, allowing for larger pressure differentials.

The use of Pd membranes for extracting hydrogen from reformer gas is investigated with the goal of reducing cost. The quality of the experimental approach is outstanding and provides a well-characterized system that can be used for fundamental studies as well as sustained engineering development. The researchers' understanding of the underlying issues is excellent, as are the qualifications of the personnel for making advances in both science and engineering. The experimental approach leads the project at present, although modeling aspects could be brought to bear for predicting hydrogen transfer rates and strain based on pressure differences, among other design issues. It may be important to extend knowledge of mechanisms associated with Pd crystal size, diffusion path through crystals versus grain boundaries, lifetime issues that might be associated with crystal ripening, and alloying effects with the support structure that may lead to degradation on the reformer gas side. There is an extensive literature on Pd membranes and their use in exploring reaction mechanisms associated with surface hydrogen. The present project could be expanded significantly to applications well beyond the one used here for purification.

Thermophotovoltaic Energy Conversion Director's Strategic Initiative (DSI)

This is an ambitious project that integrates multiple components, each of which is well-studied in the classic literature and each of which is capable of improvement. The effort benefits from vigorous pursuit with excellent insights based on knowledge of the basic phenomena that are involved. The experimental design and fabrication is excellent and makes possible, in principle, a wide variety of system parameters (for example, geometry, flow rates, emitting surfaces, and spectra filters). The reaction engineering of the combustion is treated quantitatively, while the remaining components are at present characterized as qualitative. There is a good mix of experiment and early-stage modeling, and there is significant potential for improved quantitative modeling and optimization.

Exploiting Drop Resonance for Improved Condensation

In this project, experiments are carried out on vertical copper surfaces. The quality of the experimental arrangement is good, and the data measurement methods are reliable. There is an extensive literature on heat transfer in dropwise condensation, as well as on the effect of surface movement on droplets, that has yet to be brought into the project. The effect of vertical height is also important, because droplets that detach from the upper region will clear a path as they detach and sweep up additional droplets on their way down the surface. Copper forms an oxide surface, which could represent a significant variable that needs to be characterized. Similarly, the use of surfactants is critical, because they influence contact angle and propensity of the droplets to shear. While the project is still in the early stages of development, it would benefit from more detailed consideration of the underlying physical phenomena and selection of well-characterized materials for assembling the experiment. There is great potential for significant improvements in modeling and engineering correlations for predicting heat transfer rates.

Phase Change Thermal Buffering for Army Systems

The use of latent heat from phase changes to reduce cooling demand during transient heat loads is investigated in this project. This is an excellent project with an experienced investigator. It benefits from deep understanding of fundamentals across a very wide range of materials and phase-change applications, many of which are described in the literature. Numerical simulations of transient effects play a useful role in modeling transient melting fronts. The project provides a path forward for identifying improved materials with characteristics suitable for Army applications.

Integrated Thermal Solutions for Electronics Systems

In this project configurations for improved heat transfer for various types of electronic packages are investigated by means of simulation models. Chip configurations include 3D chip stacks and power chip stacking. Various levels of sophistication of modeling methods using commercial packages were developed in order to identify the most numerically efficient methods. The quality of the work and the understanding of the underlying physical and numerical methods are excellent. There is an excellent match with practical aspects of reducing the work to practice that involves knowledge of the application as well as the heat transfer fluids and materials. While the Army may have unique applications, it is likely that there are approaches reported in the literature that can be brought to bear, provided that there is in-house expertise of the quality represented in this project.

Advanced Thermal Interphase Testing and Development

This laboratory tour demonstrated that experimental methods are being designed to accurately measure temperature drops (ΔTs) that occur across interfaces. In many energy systems when multiple interfaces exist, it is important to take into account such ΔTs, because they dictate the overall heat rejection rates.

Modified Model for Improved Flow Regime Prediction in Internally Grooved Tubes

Heat transfer during two-phase flow in small-diameter grooved tubes is investigated in this project. This is an important project that has a wide range of specific applications, requiring that the development of general knowledge of flow regimes and associated heat transfer correlations be obtained. The experimental arrangement is excellent, as are the qualifications of the personnel for experimental work. There is an extensive literature on two-phase flow in large pipeline systems as well as small-scale refrigeration systems, from which additional ideas for experimental design and analysis could be extracted. In some flow regimes associated with two-phase flow in large pipelines, the sophistication of the computational modeling has improved to the extent that it has replaced experimental measurements. While the knowledge of underlying behavior in small-scale systems is presently at an early stage of development, the path forward could include a quantitative modeling component that might grow in time.

Photonic Materials and Devices

Electromagnetic Modeling of Resonant Quantum-Well Infrared Photodetector Structures

The achievements of this project are remarkable. Twenty-five years after the invention of quantum-well infrared photodetectors (QWIPs), the work described amounts to a rebirth of the field. This work also comprises one of the most convincing applications of plasmonic enhancement for real, deployable technologies that have been demonstrated. QWIPs clearly have an exciting potential to impact the Army mission, with competitive sensitivity but based on mature materials technology that can provide high uniformity and high pixel counts; they also offer the potential for low-cost foundry manufacturing.

III-V Materials for Infrared

The investigations into narrow direct bandgap III-V materials constitute one of the best projects in the Electro-Optics and Photonics Division. As a whole, this work could radically alter the applications and deployment of mid-IR detectors and focal plane arrays, with performance equal to or better than HgCdTe, because the energy band properties are likely to be more favorable to reduced dark current. Surface recombination and passivation are easier for InAs than for GaAs or InP, so this might provide additional performance advantages.

The presentation of this project was particularly outstanding, with the research very clearly put in context and the ARL contribution compellingly told. This included the history, the probable source of historical scientific confusion in the literature, and the role of compositional ordering. This team deserves commendation for leveraging the Small Business Technology Transfer (STTR) resources to further their Auger characterization capabilities, and the team is looking forward to carrier lifetime and preliminary device results in the coming year.

This work is an outstanding example of the ways in which ARL makes unique contributions. The project's success reflects a combination of insight, effective modeling, motivation, and carefully selecting the right epitaxy technology to realize a real breakthrough in technology for Army applications.

Metamaterials and Metastructures Director's Strategic Initiative

This research activity illustrated two applications of novel integrated photonics. In the work on slow-light waveguides, the innovative designs required very challenging fabrication techniques, and the results were quite impressive. Nonetheless, performance targets were not articulated clearly enough to assess the promise or efficacy of chip-scale slow-light devices. Additionally, the fact that the results differed by a factor of 10 from the model suggests an opportunity for discovery, or that discrepancies need to be more seriously addressed.

In the work on tunable metamaterials with active adjustable bias structure, insufficient information on performance targets and results was made available to permit adequate assessment, and it is not clear if there is going to be a serious effort in terahertz (THz) applications at ARL or if this work is considered to be a basic science investigation into possible new metamaterials.

Terahertz Probe of Nitride Semiconductor Optoelectronic Materials and Devices

This project described a remarkable collection of scientific results on nitride device and materials characterization, and overall it comprised a very promising exploration of new capabilities. The presentation on the project provided a catalog of excellent achievements, but the presentation would have been more informative if it had provided more specific discussion of future directions and the most promising potential for impact. This was a good example of high-risk work, and while it may not become a mainstream characterization tool, it could provide unique capability that is not possible with other techniques.

Mid-Infrared Solid-State Laser Materials

This different method for high-power mid-IR lasers is intriguing. In particular, the elimination of thermal problems through 1.6 μ lasing is an interesting possibility. However, net quantum gain appears to be dependent on an efficient and complex combination of lasers and an optical parametric oscillator that has not yet been demonstrated. This is high-risk work from an applications perspective.

Research Presented in Posters

The work on HgCdSe materials development for GaSb substrates appears to still be limited by Se purity. The atom optics is an outstanding example of interesting but high-risk and potentially high-impact work by a strong team making steady progress in technology platform development. The heteroepitaxy of GaN on SiC appears to have demonstrated good absorption with good low-noise avalanche characteristics, claiming 75 percent QE at 240 nm; a U.S. patent has been issued. The swept frequency and other beam-combining achievements are very promising and appear to be unique and important contributions to the field. The opto-electronic oscillator (OEO) work is very strong, and the team has unraveled some interesting new acoustic effects not typically apparent in telecom applications owing to the very low frequency offsets.

OPPORTUNITIES AND CHALLENGES

Biomaterials

In previous years there was a clear lack of focus and of critical mass in the Biotechnology branch. This might be addressed with the hiring of a new branch chief. One of the important elements of developing collaborations is a leader who is well recognized in the scientific community. Therefore, in addition to the new branch chief, ARL will also need a scientifically recognized leader who can provide the scientific vision, direction, and connections to lead this program in the right direction for ARL. The Biotechnology branch will need more resources and personnel to reach critical mass. It is still a small group, which will need some time to grow and find its way. Internally, the branch could reach out to personnel inside ARL and develop joint biorelated projects, grants, and other activities. Also, it would be helpful to hire additional mid-career scientists if funding is available. In the meantime, the branch can take advantage of other Department of Defense (DoD) programs, such as the Institute for Collaborative Biotechnologies and the soldier nanotechnology programs. New interactions with other Army-supported institutes, such as the Institute for Soldier Nanotechnology at MIT, are also encouraged, and the new cooperative research and development agreement involving Johns Hopkins University, the Center for Innovative Technology, the University of Delaware, and Penn State University could be initiated.

Since the Biotechnology program is relatively new, it is premature to evaluate it against the other more mature programs (e.g., the Photonics program). It appears that the Biotechnology branch still needs a defined vision and differentiation from other laboratories and universities. Then, over time, it can become like the Photonics programs and department. The three focus areas discussed in the Biotechnology branch's presentation (biotools, biotargets, and human factors) are excellent topics that reflect a long-term, wide-ranging vision; however, these topics are still too broadly defined and will need to be further narrowed in order to benefit from current expertise at ARL. The main focus seems to be on biotools, but this was not spelled out in the general presentation. The four thrust areas mentioned in the presentations—bioinspired materials for energy, detection, and force protection; bioinspired materials for robust networks; bioinspired materials for structural awareness and evolving threats; and bioinspired materials for cognitive nanoscience and transformational medicine—are quite ambitious for a relatively small biotechnology program. Since these thrusts require a much stronger level of research commitment and resources, a further downselection and narrowing of programs that better suit the resources and capabilities of ARL is required. The Biotechnology program is not only newer but also much smaller and has fewer financial resources to build upon than its counterpart branches at ARL; however, it could make much better effort to connect to and leverage some of the strongest programs in ARL, in particular the Photonics program. The new Biotechnology branch has now a unique opportunity to refine its vision and focus it on collaboration.

The Biotechnology branch could beneficially also seek more collaboration with outside groups to define a unique place for itself with relevance to Army needs and where its researchers become leaders, not just followers. The group needs to seek new exciting areas that have direct relevance to the mission of the Army. This could be stimulated by initiating and hosting a series of quarterly seminars with the participation of leaders in the field. Of particular interest is the work being conducted at MIT on bioinspired batteries using phages and carbon nanotubes and work at Cambridge University and Imperial College London that is subjecting pig tissues and cells to impulse loading to determine the effect of shock waves. Such work could provide insight that has relevance to the mission of ARL.

Energy Materials and Devices

Increasing the use of atomistic modeling and mesoscopic (continuum) modeling represents a great opportunity to complement many of the outstanding experiments that are being performed.

The use of DFT calculations has already been useful in understanding the stability of the electrolytes, the SEI layer formation, and the development of high-voltage cathodes. In addition to DFT calculations, there is also an opportunity to conduct mesoscopic modeling of entire electrochemical systems. For instance, charge-discharge cycles of a Li-ion battery or analysis of performance characteristics of a fuel cell require solving a number of coupled equations. A comprehensive approach to system-level modeling will likely lead to new insights, which will help identify fundamental materials-related issues that in turn require further investigations. These areas offer excellent high-risk, high-reward options.

In the DFT area, considerable work is under way in other areas of ARL. It would be of value if the management of ARL could facilitate integration of these efforts. If this is not possible, perhaps ARL needs to consider hiring researchers with expertise in the computational area.

Pd membrane is another example of an opportunity. The use of Pd membranes for extracting hydrogen from reformer gas is being investigated with the goal of reducing cost. The experimental approach leads the project at present. Modeling aspects could be brought to bear for predicting hydrogen transfer rates and strain based on pressure differences, among other design issues. It may be important to extend knowledge of mechanisms associated with Pd crystal size; diffusion path through crystals versus grain boundaries; lifetime issues such as might be associated with crystal ripening; and alloying effects with the support structure that may lead to degradation on the reformer gas side. The present project could be expanded significantly to other applications well beyond the one used here for purification.

Multiple functionality of a structure appears to be another exciting area of research. The concept is to design a structural component (e.g., the wing of an aircraft) to do multiple functions. The main function is mechanical (support structure), meaning that strength, toughness, and modulus are the important properties. By designing composites with interspersed electrodes, one can also store energy as capacitors or supercapacitors.

Nonnoble metal catalysts for alkaline fuel cells also present opportunities and challenges. The objective is to synthesize organic-based catalysts containing Fe for oxygen reduction reactions. These catalysts are supported on graphene. By suitable thermal treatment, the catalyst is pyrolyzed to change its chemistry. The anode was standard carbon-supported Pt. If the performance can be improved further and stability can be demonstrated, this could represent a significant breakthrough. A computational component can further strengthen this area, specifically in catalyst design. Long-term stability of these catalysts is a challenge.

Photonic Materials and Devices

The mapping onto Army needs of some elements of the photonics portfolio appears to be quite speculative or to have a long-term horizon, and in this sense a substantial fraction of the work can be characterized as high risk. A good example of strong work in this category is the work on cold-atom optics, but there are many other examples as well.

The number of projects that are high risk in a broader context is smaller. Projects in this category would address the following questions: Will a broad investigation into a new area of study yield anything interesting? Will an unproven concept demonstrate any useful level of efficacy, independent of specific Army performance goals? The payoff for such basic work would be in finding applications for the Army at some point in the future that cannot be well-predicted today.

In this context, ARL seems to have adopted a "fast follower" approach, whereby most of the work comprises investigations into whether external scientific advances can be successfully mapped onto the Army mission. This is entirely consistent with elements of ARL's definition of innovation, but this may be more symptomatic of a predominantly top-down project selection. Other peer laboratories may have a more bottom-up approach with investigator-level risk decisions regarding entirely new approaches. The photonics work at ARL seemed to evince an aversion to risk and a low tolerance for failure.

ARL could improve the marketing of its work in the photonics area. While the story of ARL photonics can be compelling, the overviews and core competencies lists appeared to catalog activities rather than articulate capabilities, accomplishments, and impact. While the breadth of work is commendable, ARL needs to find ways to tell the world where it is truly outstanding, how it wants to be measured, and the context of its work. In many presentations of the photonics work, the connectivity to the Army-fielded technology was not strongly articulated; it would help to highlight the success stories.

There seemed to be a culture of soft-selling evident in the photonics work. For example, the recent game-changing advances in QWIP technology have catapulted ARL to a position of unambiguously being the best in the world for this technology. Presentations could include charts to show the competition, and this work could be very successfully highlighted in the international scientific community. The recent advances in narrow bandgap III-V work are also highly provocative and could be very successfully promoted in the outside technical community to raise the prestige of ARL. Businesses understand this kind of promotional activity, and ARL could emulate their approach.

OVERALL TECHNICAL QUALITY OF THE WORK

Biomaterials

The technical quality of the research and personnel in the biotechnology branch seems highly variable and ranges from good to excellent. The researchers are very knowledgeable and capable, and they have a very good understanding of the relevance of their research to Army missions. The scientists and engineers in the biomaterials area are remarkably enthusiastic and effective. Their research productivity is more than adequate in general and excellent in several areas such as applied molecular biology and biosensor development.

The photonics programs are more mature and have good projects and personnel, with a couple of projects being world-leading efforts; the biotechnology effort is newer and as such needs careful nurturing. The overall quality of the research in the biotechnology program has greatly improved over the past year and is excellent in several areas. These include the excellent research on synthetic biomolecular materials; the use of modified bacteria to study the feasibility of converting food waste to butanol; and the search for extremophile dry-tolerant, thermostable proteins for sensing applications. Several studies involving applied molecular biology are well chosen and have great potential.

Some projects reflect good underlying fundamental science; others do not involve basic understanding. If the research is conducted at ARL with outside help, systems biology could be an exciting area if it can include protein engineering, synthetic biomaterials, and extremophiles. The Biotechnology branch could closely couple with the strongly established photonics groups, which have outstanding laboratory resources and equipment. Further collaboration with outside researchers is also encouraged. For some projects, the addition of theoretical studies to accompany the experimental work will be very useful. The ARL has outstanding laboratory facilities and equipment, and the experimental research at ARL reflects the excellent work of ARL staff and efficient application of these outstanding resources. The Biotechnology branch is also well equipped to do classical molecular biology and biochemical research. The nascent systems biology and some of the computational modeling of protein structures represent some basic computational and theoretical elements of the program. However, if this branch begins to conduct research at the interface of biological and physical worlds, it would discover many opportunities for the synthesis of theoretical, computational, and experimental observations and results.

Further collaboration needs to be pursued with other research institutions, including universities, to add some theoretical studies and obtain improved fundamental understanding of the processes being investigated. Collaboration with organizations where Army-sponsored research is conducted (for example, MIT, University of California at Santa Barbara, Johns Hopkins University, and the Center for Innovative Technologies) is encouraged. These collaborations would energize the talented researchers and provide a good opportunity to conduct collaborative research and write joint papers, which would enhance the reputation of ARL in the global scientific community.

Energy Materials and Devices

The scope of the research was impressive, covering a broad spectrum of materials physics relevant to Army technologies. In general, the quality of the research reviewed was high. The quality of the scientific content of the presentations and the overall selection of topics were impressive. However, some of the specific projects presented in previous years were not presented in sufficient depth during the current review. An example is the power platform for flapping wings (microautonomous systems). Some presentation on this topic detailing its status would have been useful, especially given the significant focus on it the last couple of years.

Overall, in the materials sciences discipline, the quality of the scientific research is excellent, reflecting a broad understanding of the underlying science. There was more effort devoted to understanding and monitoring global research activities than in previous years. Increased collaboration with external organizations within the DoD community, in the industry, and in the academic community is also notable.

The question on the mix of low-risk and high-risk research to reach an optimal balance continues to be a discussion item. Nonetheless, the project portfolio does indicate a wide array of work embracing high-risk and lesser-risk research.

Photonic Materials and Devices

The science and technology in this area are strong, with some examples of world-class, breakthrough work. As exhibited in the posters and presentations, technical work is outstanding, demonstrating both the breadth and depth of work at ARL. The researchers showed clear and deep understanding of their fields, and they evinced understanding of their work both in the context of its applications potential as well as on the world research stage.

7

Crosscutting Recommendations

The metrics through which ARL, as a research organization, internally measures and quantifies the quality of its S&T research across the spectrum of its mission space were not provided to the ARLTAB. The options could include the number and impact factor of publications or the number of transitions to operational use by the warfighter. Definition of such metrics and any relevant data could enhance the impact of the ARLTAB assessments.

The mix of low-risk and high-risk research to achieve an optimal balance continues to be a crosscutting issue for all of ARL's S&T programs. ARL indicated that 30-50 percent of Director's Research Initiative (DRI) projects and many Director's Strategic Initiative (DSI) projects go on to become core efforts.[1] While ARL is looking for ways to encourage innovation that will impact mission-critical programs, making it safe to fail is one such way to encourage innovative, high-risk projects. Internal research investments in successful innovations and high-risk research expectations are goals in conflict. Risky research is likely to fail most of the time. If success is expected of nearly all projects supported by discretionary funds, staff cannot be expected to propose risky ones. Strategic management discussion of the objectives and expectations for DRI and DSI projects and how these precious funds are aligned or feed longer-term programmatic efforts is encouraged.

The visibility of ARL staff in professional technical societies and technical conferences is not up to the level that their accomplishments and scientific expertise warrant. While it is clear that the sequestration and travel restrictions have negatively affected staff interactions with the outside R&D community, the long-term continuation of restrictions on external technical interactions will have a significant adverse impact. Lack of interactions normally fostered through conferences and professional associations will negatively impact both collaborative programmatic efforts and maintenance of an edge in areas of expertise. This has clearly already affected ARL staff morale, produced opportunity costs, and will seriously impact staff retention and hiring in the future. Moreover, ARL's strategic focus on innovation through adoption and development of scientific ideas and insights from the scientific community cannot be applied to solve Army problems if the focus is solely inward. If sustained, a not-invented-here syndrome will be nearly impossible to avoid, leading to internal reinvention of wheels that would be better brought in from outside.

Steps to improve the overall ARL research enterprise include the following:

Recommendation 1. ARL should require researchers to clearly articulate the existing technical challenges in their research and how and why proposed tools and methods are likely to resolve those challenges.

Recommendation 2. To allow for setting meaningful goals and adopting a research agenda that targets nonincremental advances, ARL should require all researchers to identify precise metrics against which progress can be gauged.

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[1] ARL uses the DSI and DRI research projects to build new research capabilities in long-term, high-risk scientific areas with very high potential payoff to the Army mission. DSI projects are typically $500,000 to $1 million per year, while DRI projects are $250,000 per year.

Recommendation 3. As ARL continues to build its research staff, it should give some attention to bringing in mid-career and senior personnel to mentor the outstanding early-career scientists who have been recruited.

Recommendation 4. ARL should look for additional ways to increase interaction of its researchers with leaders in industry and academia, given that limitations on travel have restricted this important function.

Recommendation 5. ARL should focus on developing a mature framework to guide the conception, design, development, and testing of small, unmanned autonomous systems, including definitions of pertinent parameters and their domain (values).

Recommendation 6. ARL should adopt a systems integration approach as a fundamental research thrust.

As the intersection of modeling and simulation with experimental measurements grows, it requires a coherent treatment of verification and validation across ARL. Model validation was insufficiently defined and elucidated during the review for the majority of the projects presented. Some excellent examples of validation were shown, such as in the MOUT project, but this was not seen throughout the review. Too often, a computer-based visualization of a model was presented with little or no quantitative comparisons to data. Details of complex material and structural models matter, but these, along with the basis for choosing model parameter values, were seldom discussed. When geometry or assumptions of material behavior are considerably simplified, it is important to provide data justifying such approximations. The success of a model in reproducing a visual image of the overall phenomenology is not validation. To map out regions to define and limit experiments, delineation is needed on a project by project basis as to whether validation is sought via a detailed comparison with quantitative data or via the ability to predict trends in response or in performance. A rigorous formal internal validation program is needed within ARL to quantify whether the physics within the broad spectrum of ballistics models being developed accurately describes the operative physics. Given the importance of such models to the development of predictive design capability in support of current Army programs and future system, platform, and equipment development, increased emphasis on validation is warranted. In addition to the need for an ARL-wide strategic approach to model validation, methods are needed to quantify the margin of uncertainty (QMU) for these models. For example, it is not clear how the operational requirements-based casualty assessment (ORCA) and MUVES-S2 models are validated. The reviews often lack sufficient details on how ARL's models are formulated and validated; the sensitivity, if known, to key parameters and variables; and the statistical variations to be expected.

The details of how ARL is leveraging ARO's 6.1 investment in support of the near-term and long-term Army strategic vision was not always clearly presented to the ARLTAB panels. Examples of how individual ARO projects fit into Army overall goals and relate to one another and to other ARL projects would facilitate the ARLTAB's tasking, to assess the quality of ARL's S&T.

Appendixes

A

Army Research Laboratory Organization Chart

Figure A.1 is an organization chart for the Army Research Laboratory (ARL), and Table A.1 maps the ARL organizational chart to the core competency areas reviewed in 2013.

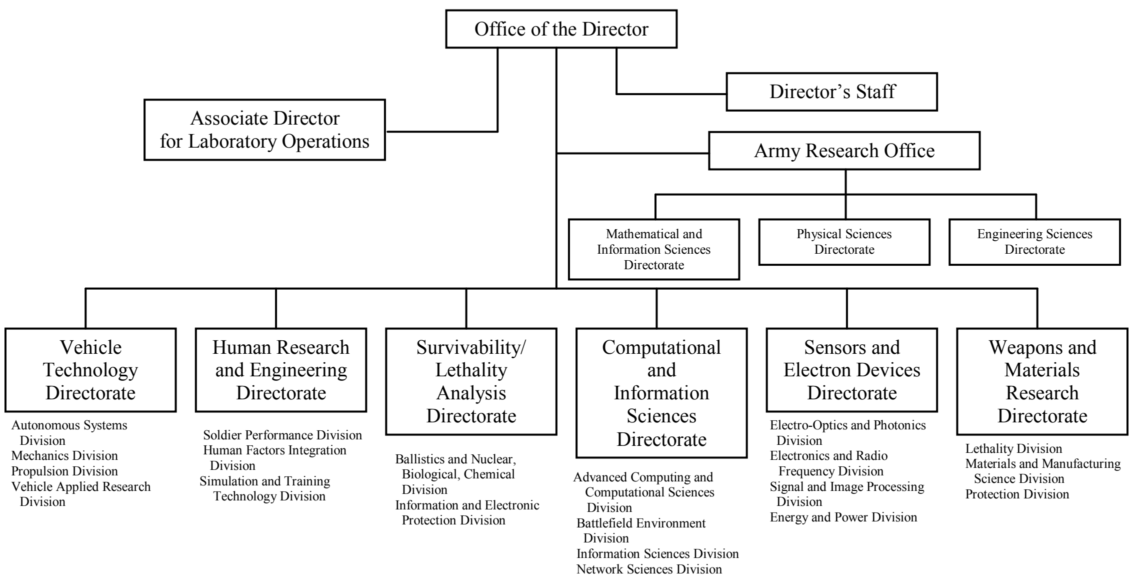

FIGURE A.1 Army Research Laboratory organization chart.

TABLE A.1 Mapping of the ARL Organization Chart to the Core Competency Areas Reviewed in 2013

Core Competency Area	2013 Topic	ARL Directorate Involved
Materials sciences	• Energy materials and devices • Photonic materials and devices • Biomaterials	SEDD, WMRD
Ballistic sciences	• Terminal ballistics	WMRD, SLAD, HRED, SEDD
Information sciences	• Autonomous systems	VTD, CISD, SEDD, HRED
Human sciences	• Transitional neuroscience • Soldier simulation and training technology	HRED, SEDD, SLAD

B

Biographical Sketches of Army Research Laboratory Technical Assessment Board Members and Staff

R. BYRON PIPES, *Chair,* NAE, has been the John Leighton Bray Distinguished Professor of Engineering at Purdue University since 2004. He is a member of the Royal Society of Engineering Sciences of Sweden (1995). Composite materials have been the focus of his scholarship for the past 44 years. He has developed analytical models and carried out experiments with the objective of developing a fundamental understanding of the design, durability, and manufacture of these materials systems and structures. He served as Goodyear Endowed Professor of Polymer Engineering at the University of Akron from 2001 to 2004. He was Distinguished Visiting Scholar at the College of William and Mary during 1999-2001, where he pursued research in carbon nanotechnology at the NASA Langley Research Center. He served as president of Rensselaer Polytechnic Institute from 1993 to 1998. Dr. Pipes was provost and vice president for academic affairs at the University of Delaware from 1991 to 1993 and served as dean of the College of Engineering and director of the Center for Composite Materials in 1977-1991 at the same institution. He was appointed Robert L. Spencer Professor of Engineering in 1986 in recognition of his outstanding scholarship in the field of polymer composite materials ranging over the subject areas of advanced manufacturing science, durability, design, and characterization. Dr. Pipes received his Ph.D. degree in mechanical engineering from the University of Texas at Arlington and the M.S.E. from Princeton University. He is the recipient of the Gustus L. Larson Award of Pi Tau Sigma and the Chaire Francqui, Distinguished Faculty Scholar Award, in Belgium. He is a fellow of ASC, ASME, and SAMPE.

KENNETH R. BOFF is principal scientist with Socio-Technical Sciences. From 2007 to 2012, he served as principal scientist with the Tennenbaum Institute at the Georgia Institute of Technology and as scientific advisor to the Asian Office of Aerospace Research and Development (Tokyo). From 1997 to 2007, he served as the U.S. Air Force Research Laboratory chief scientist for human effectiveness. In this position was responsible for the technical direction of a multidisciplinary R&D portfolio encompassing individual, organizational, and sociocultural behavior and modeling, training, protection, and the bio- and human engineering of complex systems. He is best known for his work on understanding and remediating problems in the transition of research to applications in the design, acquisition, and deployment of systems and the value-centered management of R&D organizations. Holder of a patent for rapid communication display technology, Dr. Boff has authored numerous articles, book chapters, and technical papers and is coeditor of *Organizational Simulation* (2005) and *System Design* (1987); he is also senior editor of the two-volume *Handbook of Perception and Human Performance* (1986) and the four-volume *Engineering Data Compendium: Human Perception and Performance* (1988). He actively consults and provides technical liaison with government agencies, international working groups, universities, and professional societies. He has organized and facilitated numerous technical workshops in the United States, Europe, and the Pacific Rim focused on contemporary issues in complex sociotechnical systems. He is a fellow of the Human Factors and Ergonomics Society and the International Ergonomics Association.

EPHRAHIM GARCIA is a professor and director of graduate studies for the field of aerospace in the

Department of Mechanical and Aerospace Engineering at Cornell University. His area of expertise is dynamics and controls, especially sensors and actuators involving smart materials with applications to robotics, energy harvesting, and bioinspired machines. Dr. Garcia served as a program manager in the Defense Sciences Office at the Defense Advanced Research Projects Agency (DARPA) from 1998 to 2002. His programs involved the development of new types of actuation systems utilizing smart material transducers, system-level demonstrations of smart structures applied to defense platforms, morphing aircraft systems, and the development of exoskeletons for human performance augmentation. From 1991 to 1998, Dr. Garcia was an assistant and then associate professor of mechanical engineering at Vanderbilt University, where he was director of the Center for Intelligent Mechatronics and the Smart Structures Laboratory. In this capacity he directed research in the areas of smart structures, control-structure interaction, and bioinspired robotics. From 1991 to 1997, he owned and operated Garman Systems, Inc. (now Dynamic Structures and Materials, LLC), a small engineering corporation that designed and fabricated devices in adaptive structural systems using smart materials. In 1995, Dr. Garcia was named an Office of Naval Research Young Investigator and appointed a 1993 Presidential Faculty Fellow by President Clinton. Dr. Garcia is author of more than 275 articles, book chapters, edited volumes, and books. In 2002, he received the prestigious American Society of Mechanical Engineers' Adaptive Structures Prize for "significant contributions to the sciences and technologies associated with adaptive structures and/or materials systems." Since 2006, he has served as editor in chief of the *Smart Materials and Structures* journal. Dr. Garcia is a fellow of the Institute of Physics and the American Society of Mechanical Engineers and an associate fellow of the American Institute of Aeronautics and Astronautics.

GEORGE T. (Rusty) GRAY III is a laboratory fellow and staff member in the dynamic properties and constitutive modeling team within the Materials Science Division of Los Alamos National Laboratory. He came to LANL following a three-year visiting scholar position at the Technical University of Hamburg-Harburg in Hamburg, Germany, having received his Ph.D. in materials science in 1981 from Carnegie Mellon University. As a staff member (1985-1987) and later team leader (1987-2003) in the Dynamic Materials Properties and Constitutive Modeling Section within the Structure/Property Relations Group (MST-8) at LANL, he directed a research team working on investigations of the dynamic constitutive and damage response of materials. He conducts fundamental, applied, and focused programmatic research on materials and structures, in particular in response to high strain rate and shock deformation. His research is focused on experimental and modeling studies of substructure evolution and the mechanical response of materials. He is a Life Member of Clare Hall, Cambridge University, where he was on sabbatical in the summer of 1998. He is a fellow of the American Physical Society, ASM International, and the Minerals, Metals, and Materials Society (TMS). He serves on the International Scientific Advisory Board of the European DYMAT Association. In 2010 he served as the president of TMS. He has authored or coauthored more than 380 technical publications.

PRABHAT HAJELA is provost and professor of mechanical and aerospace engineering at the Rensselaer Polytechnic Institute. His 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 seven years. He has conducted research at NASA's Langley and Glenn Research Centers and 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 boards of six other international journals. He has published over 270 papers and articles in the areas of structural and multidisciplinary optimization and is an author or coauthor of four books in these areas. In 2004, he was the recipient of AIAA's Biennial Multidisciplinary Design Optimization Award.

JENNIE S. HWANG, NAE, is chief executive officer of H-Technologies Group and board trustee and distinguished adjunct professor at Case Western Reserve. Her career encompasses corporate and entrepreneurial businesses, international collaboration, research management, technology transfer, and global leadership positions, as well as corporate and university governance. She has held senior executive positions with Lockheed Martin, SCM Corporation, and Sherwin Williams and has cofounded entrepreneurial businesses. She is internationally recognized as a pioneer and long-standing leader in the fast-moving infrastructure development of electronics miniaturization and green manufacturing. Dr. Hwang is an inventor and author of 350+ publications, including the sole authorship of several internationally used textbooks. As a columnist for the globally circulated trade magazines *Global Solar Technology* and *SMT*, she addresses technology issues and global market thrusts. She also has served on the International Advisory Board of the Singapore Advanced Technology and Manufacturing Institute and as a board director for Fortune 500 and private companies. Over the years, she has taught tens of thousands of professionals and managers in professional development courses, providing the continuing education and disseminating new technologies to the workforce. The YWCA's Dr. Jennie S. Hwang Award was established to encourage and recognize outstanding women students in science and engineering. Her formal education includes the Harvard Business School Executive Program, a Ph.D. in materials science and engineering, two M.S. degrees, one in chemistry and one in liquid crystal science, and a bachelor's degree in chemistry.

Staff

LIZA HAMILTON is the administrative coordinator for the Laboratory Assessments Board in the Division on Engineering and Physical Sciences at the National Research Council (NRC). Since 2002, she has been responsible for managing the administrative aspects of panel formation, panel meetings, report publication and dissemination, and program development. In addition, she has designed newsletters, brochures, covers, and figures for numerous reports prepared by the NRC's Division on Life Sciences and its Division on Engineering and Physical Sciences. Ms. Hamilton earned a four-year certification in musical theater performance from Pinellas County Center for the Arts in St. Petersburg, Florida; a B.F.A. in film studies from the University of Utah; a design certification from Maryland Institute College of Art; and the master of liberal arts from the Johns Hopkins University.

EVA LABRE is the program associate for the Laboratory Assessments Board in the Division on Engineering and Physical Sciences at the NRC. Since 2009, she 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. Ms. Labre previously held administrative positions on the staff of the Committee on International Organizations and Programs in the NRC Office of International Affairs and on the staff of the Research Associateship Program in the NRC 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 Laboratory Assessments Board, the Army Research Laboratory Technical Assessment Board (ARLTAB), and the Committee on National Institute of Standards and Technology Technical Programs, in the Division on Engineering and Physical Sciences at the NRC. Since 1994, he has been a senior staff officer at the NRC, directing projects in the areas of systems engineering and applied psychology, including activities of 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 NRC projects on air traffic control automation, musculoskeletal disorders and the workplace, and the changing nature of work. Prior to joining the NRC, 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 Laboratory Assessments Board in the Division on Engineering and Physical Sciences at the NRC. Since 1999, he has been a senior program officer at the NRC, directing projects in the areas of defense science and technology, including those carried out by numerous study committees of the Laboratory Assessments Board, the Army Research Laboratory Technical Assessment Board, the Naval Studies Board, and the National Materials and Manufacturing Board. Prior to joining the NRC, Dr. Mozhi held technical and management positions in systems engineering and applied materials research and development at UTRON, Inc.; Roy F. Weston, Inc.; and Marko Materials, Inc. He received his M.S. and Ph.D. degrees (the latter in 1986) in materials engineering from the 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's (ARLTAB's) assessment considered the following general 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/or 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/or 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 will also consider 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 the ARL:

1. Effectiveness of Interaction with the Scientific and Technical Community
   a. Papers in quality refereed journals and conference proceedings (and their citation index).
   b. Presentations and colloquia.
   c. Participation in professional activities (society officers, conference committees, journal editors).
   d. Educational outreach (serving on graduate committees, teaching/lecturing, invited talks, mentoring students).
   e. Fellowships and awards (external and internal).
   f. Review panel participation (ARO, NSF, MURI, and the like).
   g. Recruiting new talent into ARL.
   h. Patents and intellectual property (and examples of how the patent or intellectual property is used).
   i. Involvement in building an ARL-wide cross-directorate community.
   j. Public recognition, e.g., in the press and elsewhere, for ARL research.

2. Formulation of Projects' Goals and Plans
   a. Are tasks well defined to achieve objectives?
   b. Does the project plan clearly identify dependencies (i.e., successes depend on success of other activities within the project or outside developments)?
   c. If the project is part of a wider activity, is role of the investigators clear, and are the project tasks and objectives clearly linked to those of other related projects?
   d. Are milestones identified if they are appropriate? Do they appear feasible?
   e. Are obstacles and challenges defined (technical, resources)?
   f. Does the project represent an area where application of ARL strengths is appropriate?

3. Research and Development Methodology
   a. Are the hypotheses appropriately framed within the literature and theoretical context?
   b. Is there a clearly identified and appropriate process for performing required analyses, prototypes, models, simulations, tests, etc.?
   c. Are the methods (e.g., laboratory experiment, modeling/simulation, field test, analysis) appropriate to the problems? Do these methods integrate?
   d. Is the choice of equipment/apparatus appropriate?
   e. Is the data collection and analysis methodology appropriate?
   f. Are conclusions supported by the results?
   g. Are proposed ideas for further study reasonable?
   h. Do the trade-offs between risk and potential gain appear reasonable?
   i. If the project demands technological or technical innovation, is that occurring?
   j. What stopping rules, if any, are being or should be applied?

4. Capabilities and Resources
   a. Are the qualifications and number of the staff (scientific, technical, administrative) appropriate to achieve success of the project?
   b. Is the state of the equipment and facilities adequate?
   c. If staff or equipment are not adequate, how might the project be triaged (what technical thrust should be emphasized, what sacrificed?) to best move toward its stated objectives?

D

Acronyms

3D	three-dimensional
A2SF	advanced all-source fusion
AC&CSD	Advanced Computing and Computational Sciences Division
AC2T	academic class composite tool
ACM	Association for Computing Machinery
ADS	advanced distributed simulation
AEC	Army Evaluation Center
AFM	atomic force microscopy
AFOSR	Air Force Office of Scientific Research
AFRL	Air Force Research Laboratory
AHAAH	auditory hazard assessment algorithm for humans
AMRDEC	Aviation and Missile Research, Development and Engineering Center
AMSAA	Army Materiel Systems Analysis Activity
APS	active protection system
ARDEC	Armament Research, Development and Engineering Center
ARL	Army Research Laboratory
ARLTAB	Army Research Laboratory Technical Assessment Board
ARO	Army Research Office
ATO	Army technology objective
BCI	brain–computer interaction
BED	Battlefield Environment Division
BND	Ballistics and Nuclear, Biological, and Chemical Division
BRAC	base realignment and closure
BRL–CAD	Ballistic Research Laboratory–Computer-Aided Design
CAD	computer-aided design
CASEL	cognitive assessment, simulation, and engineering laboratory
CC	capability concept
CECOM	Communications-Electronics Command
CERDEC	Communications-Electronics Research, Development, and Engineering Center
CFD	computational fluid dynamics
CIO/G-6	Office of the Chief Information Officer
CISD	Computational and Information Sciences Directorate
CMD-P	computer meteorological data profiler
CMMI	capability maturity model integration
COTS	commercial off-the-shelf
CRA	Collaborative Research Alliance
CSD	Computational Sciences Division of the CISD

CTA	Collaborative Technology Alliance
DARPA	Defense Advanced Research Projects Agency
DE	directed energy
DFT	density functional theory
DMAZ	dimethylamino-2-ethylazide
DNS	direct numerical simulation
DoD	Department of Defense
DOE	Department of Energy
DRI	Director's Research Initiative
DSI	Director's Strategic Initiative
DU	depleted uranium
EAR	environment for auditory research
EASE	executable architecture systems engineering
ECAE	equal channel angle extrusion
ECG	electrocardiography
EEG	electroencephalogram
EFP	explosively formed penetrator
EIS	electrochemical impedance spectroscopy
EM	electromagnetic
EMG	electromyography
EMVAF	Electro Magnetic Vulnerability Assessment Facility
EOCM	electro-optic countermeasures
EO&P	Electro-optics and Photonics (Division)
EPAs	embodied pedagogical agents
ERA	explosive reactive armor
ESAPI	enhanced small arms protective inserts
FAST	field assistance in science and technology
FCS	future combat systems
FEA	finite-element analysis
FEM	finite-element modeling
fMRI	functional magnetic resonance imaging
FPGA	field-programmable gate array
FY	fiscal year
GCV	ground combat vehicle
GIFT	generalized intelligent framework for tutoring
GLEEM	gun liner emplacement by elastomeric materials
GNC	guidance, navigation, and control
GPS	Global Positioning System
GPU	graphics processing unit
GSR	galvanic skin response
GUI	graphical user interface
HP	horsepower
HPC	high-performance computing
HRED	Human Research and Engineering Directorate
HRI	human–robot interaction
HSI	human system integration

ICA	independent component analysis
ICT	Institute for Creative Technology
IED	improvised explosive device
IEEE	Institute of Electrical and Electronics Engineers
IEPD	Information and Electronic Protection Division
IGF	intergranular grain-boundary film
IM	insensitive munitions
IMPRINT	Improved Performance Research Integration Tool
IMU	inertial measurement unit
INSCOM	Intelligence Security Command
INVA/DE	integrated network vulnerability assessment/discovery exploitation
IO	information operations
IPA	Intergovernmental Personnel Act
IR	infrared
IRCM	infrared countermeasure
IRFNA	inhibited red fuming nitric acid
ISD	Information Sciences Division
ISR	intelligence, surveillance, and reconnaissance
ITA	International Technology Alliance
JP-8	jet propellant 8 (fuel)
KE	kinetic energy
LED	light-emitting diode
LES	large-eddy simulation
LIF	laser-induced fluorescence
LIFE	laser IRCM flyout experiment
Li-ion	lithium ion
LWIR	long-wavelength infrared
M&S	modeling and simulation
MADIS	meteorological assimilation data ingest system
MANPRINT	manpower and personnel integration
MASINT	measurement and signature intelligence
MAST	micro-autonomous systems and technology
MBT&E	mission-based test and evaluation
MEDE	materials in extreme dynamic environments
MEMS	microelectromechanical systems
MMF	Mission and Means Framework (software)
MOUT	military operations on urban terrain
MRAP	mine-resistant ambush-protected
MSME	multiscale multidisciplinary modeling of electronic materials
MT	machine translation
MURI	Multidisciplinary University Research Initiative
MUVES	Modular UNIX-based Vulnerability Estimation Suite (software)
NASA	National Aeronautics and Space Administration
NC	nanocellulose
NDE	nondestructive evaluation
NERA	nonexplosive reactive armor

NLOS	non-line-of-sight
NMR	nuclear magnetic resonance
NOAA	National Oceanographic and Atmospheric Administration
NRC	National Research Council
NSD	Network Sciences Division
NSF	National Science Foundation
NWS	National Weather Service
OA	optical augmentation
OCR	optical character recognition
ODE	ordinary differential equation
ODR	opportunity-driven research
ODT	omnidirectional treadmill
OEO	opto-electronic oscillator
ONR	Office of Naval Research
ORCA	operational requirements-based casualty assessment
OSD	Office of the Secretary of Defense
PASS	personal academic strategies for success
PDV	photon doppler velocimetry
PFM	phase field modeling
PSL	Physical Sciences Laboratory (at New Mexico State University)
PTSD	post-traumatic-stress disorder
QAM	quadrature amplitude modulation
QE	quantum efficiency
QMU	quantify the margin of uncertainty
QWIP	quantum-well infrared photodetector
R&D	research and development
RDEC	Research, Development, and Engineering Center
RDECOM	Research, Development, and Engineering Command
RF	radio frequency
RTDS	real-time digital simulator
S&T	science and technology
S4	System-of-Systems Survivability Simulation (software)
SAFTE	sleep, activity, fatigue and task effectiveness
SBAM	scalable binary annular munition
SBIR	small business innovation research
SEDD	Sensors and Electron Devices Directorate
SEI	solid electrolyte interface
SEMACS	specialty electronics, materials, and sensors (program)
SiC	silicon carbide
SiC-N	silicon carbide-new
SIRE	Synchronous Impulse Reconstruction
SLAD	Survivability/Lethality Analysis Directorate
SLAM	simultaneous localization and mapping
SLV	survivability, lethality, and vulnerability
SLVA	survivability, lethality, and vulnerability assessment
SME	subject-matter expert

SNA	social network analysis
SOFC	solid oxide fuel cell
SoS	system-of-systems
SoSA	system-of-systems analysis
SPEAR	soldier performance and equipment advanced research
STTC	Simulation and Training Technology Center
STTR	small business technology transfer
STEM	science, technology, engineering, and mathematics
SWaP	space, weight, and power
T&E	testing and evaluation
TARDEC	Tank Automotive Research, Development, and Engineering Center
TBI	traumatic brain injury
TEM	transmission electron microscopy
THINK	tactical human integration of networked knowledge
THz	terahertz
TILV	target interaction lethality/vulnerability
TMEDA	N,N,N′,N′-tetramethylethylenediamine
TN	translational neuroscience
TNT	2,4,6-trinitrotoluene
TRAC	Training and Doctrine Command Analysis Center
TRADOC	Training and Doctrine Command
TTPs	tactics, techniques, and procedures
TTR	through-thickness reinforcement
TWV	tactical wheeled vehicle
UAS	unmanned autonomous system
UAV	unmanned aerial vehicle
UBB	underbody blast
UGV	unmanned ground vehicle
UV	ultraviolet
V&V	validation and verification
VAATE	Versatile Affordable Advanced Turbine Engines (program)
VAPP	very affordable precision projectile
VARD	Vehicle Applied Research Division
VBS2	Virtual Battlespace 2
VSL	virtual shot line
VTD	Vehicle Technology Directorate
VTOL	vertical takeoff and landing
WC	tungsten carbide
WEL	Wireless Emulation Laboratory
WFO	warfighter outcome
WHA	tungsten heavy alloy
WIAMan	warrior injury assessment manikin
WMRD	Weapons and Materials Research Directorate
WRF	weather research and forecast