DEVCOM
ARMY RESEARCH LABORATORY

HIGH-PERFORMANCE
COMPUTING
REVIEW

2018 - 2019

Content

Message from

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the Directors

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Since the inaugural issue of our biannual Army Research Laboratory (ARL) High Performance Computing Review last year, many changes have affected our Department of Defense (DOD) Supercomputing Resource Center (DSRC). We are now the Combat Capabilities Development Command (CCDC) ARL, a part of the new Army Futures Command. ARL's missions are to deliver the scientific knowledge for future concepts; discover, develop and integrate overmatch capabilities for Soldiers; and provide technological expertise for state-of-the-art warfighter systems. We must achieve this at the speed and scale required to attain or maintain overmatch for multi-domain operations. We are expanding our emphasis on autonomous systems, artificial intelligence, and machine learning, as well as the computational and data sciences needed to support these key research efforts. The DSRC is stepping out in each of these new areas, while maintaining our traditional support for physics-based modeling and simulation.

The year 2019 witnessed another big change; my selection of Mr. Matt Goss to lead the ARL DSRC. Matt comes to us from the test and evaluation community and brings with him a range of experience from across the Army acquisition enterprise. He brings not only a new leadership approach but also a passion for customer support, and a drive to care for our ultimate customer, the soldier.

I welcome you to the ARL DSRC. There are many changes, indeed, and I'm very happy to be a part of this amazing organization! I look forward to collaborating with our community to enhance and accelerate weapon systems development through high performance computing. The entire DSRC team remains eager to assist our customers in modernizing our Army and protecting our troops!

The High Performance Computing (HPC) Modernization Program (HPCMP) Technology Insertion for FY18 (TI-18) brought us a Cray CS500 in late calendar 2019. In honor of Frances Elizabeth "Betty" (Snyder) Holberton, one of the original ENIAC programmers, we have nick-named it "Betty." The CS500 consists of 102,400 AMD EPYC (Rome) cores with a total of 446 terabytes of RAM, 15 petabytes of RAID storage and 350 terabytes of SSD. It also offers 292 NVidia Volta V100 general purpose graphics processing units.

Also arriving at the end of 2019 was the first mobile, deployable HPC in the Program, SCOUT, a 6 petaFLOPS IBM POWER9 architecture housing NVidia V100 GPUs. It is tailored for autonomous systems and AI/ML workloads. Along this same line, we have undertaken, in concert with the HPCMP, an extensive requirements gathering process in support of TI-20. With the drive toward autonomous systems and their inherent dependence on machine learning and large-scale data analytics, we are trying to understand not only our current customer needs, but also the needs of other, non-traditional audiences that could be future HPC customers. The ARL DSRC and HPCMP staffs will ensure the next generation of HPCs are fully capable of supporting the DoD community in solving the hardest scientific questions for the future of our military.

Our Mission, Our Vision

Accelerate The Army Of The Future

The CCDC Army Research Laboratory is the Army's corporate research laboratory. ARL conducts foundational research to drive change – new paradigms, new ideas, new innovations within, across and between disciplines. The CCDC Mission is to provide the research, engineering, and analytical expertise to deliver capabilities that enable the Army to deter and, when necessary, decisively defeat any adversary now and in the future. Our vision is that computational science and the applications of advanced computing technologies will accelerate Army modernization through targeted research guided by integration with Army Cross Functional Teams which support the six Army modernization priorities: Long-Range Precision Fires, Next-Generation Combat Vehicles, Future Vertical Lift, Army Network, Air and Missile Defense, and Soldier Lethality. ARL fosters disruptive research that will not only help inform Army colleagues about the nature of the future fight, but will change the way people think about science, concepts and warfighting. One of the overarching themes of modernizing the Army is speed of delivery — delivering capabilities to Soldiers more quickly.

The U.S. Army Combat Capabilities Development Command, has established Team Ignite to assist the command in further shaping disruptive concepts and capabilities for future warfighting. The goal is to move from our current state of scientific research and concept development that is conducted and governed independently, to established mechanisms and processes to effectively consume innovation, scientifically informed concepts and warfighter informed scientific research projects and investments. This will accelerate CCDC support to Multi Domain Operations. Multi-Domain Operations is how the Army, as part of the joint force, will solve the problem of layered standoff in all domains -- land, sea, air, space, and cyberspace.

The Army Research Laboratory is also investing in the future workforce, for example, through the HPCMP Internship Program (HIP)

*ARL DSRC's two new systems BETTY (top) and SCOUT (bottom)*

and the Army Educational Outreach Program (AEOP). The HIP provides experience to prospective DoD employees in defense-related research and development and develops the next-generation workforce in an active and collaborative effort among the HIP Mentors/Supervisors, HIP Interns, and the HIP Program Manager. The AEOP offers our nation's youth and teachers a portfolio of opportunities that effectively engage future workforce generations in meaningful, real-world Science, Technology, Engineering and Mathematics experiences, competitions and paid internships. The demand for qualified scientists and engineers, and indeed the full array of skills required to execute the mission of the Army Research Laboratory, is greater than ever and the Army is actively pursuing innovative approaches for attracting and retaining the future workforce.

Why Army Research?

The CCDC Army Research Laboratory is an element of the U.S. Army Combat Capabilities Development Command. As the Army's corporate research laboratory, ARL discovers, innovates and transitions science and technology to ensure dominant strategic land power. Through collaboration across the command's core technical competencies, CCDC leads in the discovery, development and delivery of the technology-based capabilities required to make Soldiers more lethal to win our Nation's wars and return home safely. CCDC is a major subordinate command of the U.S. Army Futures Command, which utilizes the best expertise, whatever the source, to create innovative solutions faster and better in the quest to modernize the way the Army does business. The Army Futures Command makes sure Soldiers have what they need, before they need it, to protect tomorrow... today.

The Army's Multi-Domain Operation strategy will require advanced autonomous systems to exploit freedom of maneuver on the future battlefield. These autonomous systems will require behaviors that enable scaling to large collaborative heterogeneous teams, intelligent systems that can reason and manipulate the environment at operational speeds and employ explainable and verifiable actions. The research, development and analysis that CCDC delivers is critical to delivering these required capabilities.
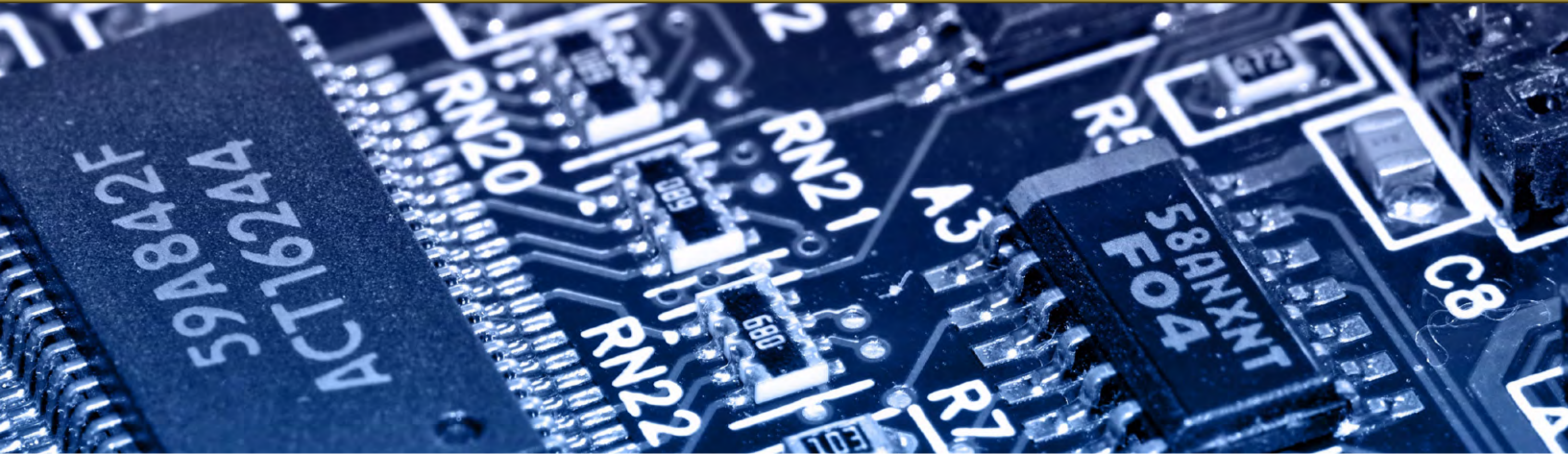
Facilities

Army Research Laboratory Supercomputing Research Center

The Supercomputing Research Center is the Army's premier advanced computing facility, consisting of the ARL Computational and Information Sciences Directorate and the DSRC. This confluence of basic and applied research expertise and facilities is the key to unlocking basic physical phenomena and harnessing the potential for defeating future threats and protecting U.S. personnel and property.

The ARL DSRC is one of five DOD HPC centers provided by the HPCMP and hosts un-classified and classified computing platforms and storage. Combined with HPC soft-ware, secure broadband networks, data storage, and subject matter expertise, it is a powerful tool for research, discovery, innovation, problem solving, and creation and sustainment of future weapon systems

Defense Research and Engineering Network (DREN)

The Defense and Research Engineering Network (DREN) is the HPCMP's broadband network supporting the S&T, Test and Evaluation, and Acquisition communities. It is high speed, high capacity, low latency, and nationwide providing access to the DSRCs by DOD, industry and university partners.

Root Name Server

ARL hosts one of 13 global root name servers, a critical element of the internet infrastructure. The ARL H root server is one of only three operated by the Federal government, the other two hosted by the Defense Information Systems Agency and NASA Ames Research Center, respectively. All others are hosted by industry or universities. Root name servers are the first stop in translating (resolving) human readable host names into machine readable internet protocol (IP) addresses used in communications among hosts and devices. The ARL root name server legacy dates back to the original ARPANET.

Computational Systems

BETTY
Cray CS500
102,400 2.9 GHz AMD (EPYC) Rome Cores
446 TB System Memory
350 TB NVMe Solid State Drive
15 PB RAID Storage
GPUs: 292 NVIDIA Volta V100
Interconnect: HDR InfiniBand
Operating System: Red Hat Enterprise Linux

SCOUT
IBM Power9
22 Training Nodes
    132 NVIDIA V100 GPUs
    11 TB Memory
    330 TB Solid State Storage
128 Inference Nodes
    512 NVIDIA T4 GPUs
    32 TB Memory
    512 TB Solid State Storage
Interconnect: EDR InfiniBand
Operating System: Red Hat Enterprise Linux

CENTENNIAL
SGI ICE XA
73,920 2.2 GHz Intel XEON Cores
253 TB System Memory
12 PB RAID Storage
GPUs: 56 NVIDIA K40 Tesla
Interconnect: Enhanced Data Rate
InfiniBand Non-Blocking Fat Tree Topology
Operating System: Red Hat Enterprise Linux

HELLFIRE
SGI ICE XA
33,088 2.2 GHz Intel XEON Cores
201 TB System Memory
3.5 PB RAID Storage
GPUs: 48 NVIDIA K40 Tesla
Interconnect: Enhanced Data Rate InfiniBand
Non-Blocking Fat Tree Topology
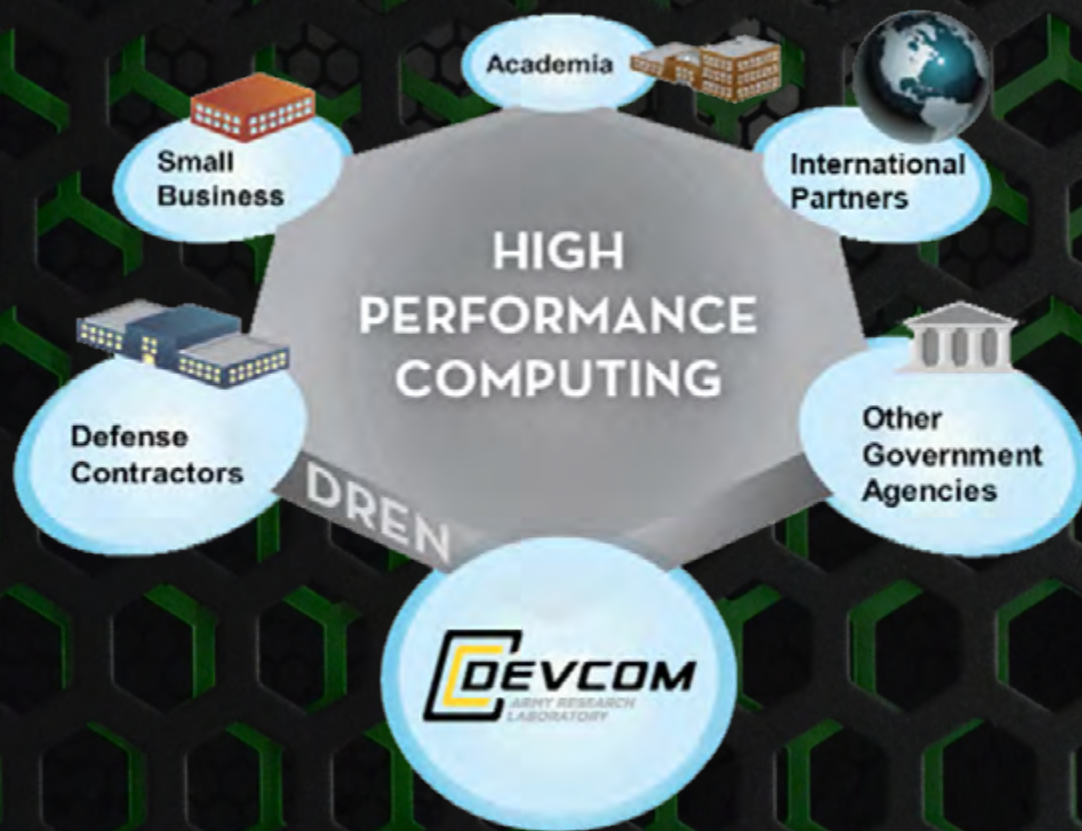Operating System: Red Hat Enterprise Linux

EXCALIBUR
Cray XC40
101,312 2.3 GHz Intel XEON Cores
411 TB System Memory
122 TB Solid State Disk
4.6 PB RAID Storage
GPUs: 32 NVIDIA K40 Tesla
Interconnect: Aries with Dragonfly
Operating System: Cray Linux Environment

Partnerships

DOD High Performance Computing Modernization Program (HPCMP)

The DOD High Performance Computing Modernization Program (HPCMP) has realized great success in establishing world-class, state-of-the-art high performance computing capabilities within the Department's laboratories and test centers since its inception in 1992. The technology-led, innovation-focused Program provides the Department of Defense with supercomputing capabilities, high-speed network communications, and computational science expertise that enable DOD scientists and engineers to conduct a wide range of focused research, development, test and acquisition activities. This partnership puts advanced technology in the hands of U.S. forces more quickly, less expensively, and with greater certainty of success. High performance computing amplifies the creativity, productivity, and impact of the workforce by giving them access to insight about the physical world, and human actions within it, that would otherwise be too costly, too dangerous, or too time-intensive to obtain through observation and experiment alone, or for which no test capability exists.

The HCPMP is implementing major strategic technology initiatives to securely deliver a spectrum of HPC capabilities and expertise for DOD RDT&E and acquisition engineering priorities. Specifically, the HPCMP is targeting Large-Scale Classified Computing; HPC at the Edge; Decision Analytics, Artificial Intelligence, Machine Learning; Support to Acquisition Engineering and Test and Evaluation; HPCMP Commercial Cloud and Open Research; and Secure Connectivity.

The HPCMP is managed on behalf of the Department of Defense by the U.S. Army Engineer Research and Development Center.

Army Artificial Intelligence Innovation Institute (A2I2)

In 2019, ARL established the Army Artificial Intelligence Innovation Institute (A2I2) with the primary goal to rapidly advance adaptive artificial intelligence (AI) capabilities for fully autonomous maneuver to support multi domain operations. Adaptive AI will learn with little or no supervision using small data sets collected organically, will quickly and easily adapt to new tasks, will provide context and understanding in unstructured environments, and will defeat attacks from adversarial machines. The Army also established a five-year Cooperative Agreement for fundamental AI research, with Carnegie Mellon leading a consortium of universities to develop robust operational AI solutions to enable autonomous processing, exploitation, and dissemination of intelligence and other critical, operational, decision-support activities, and to support the increased integration of autonomy and robotics as part of highly effective human-machine teams.

To support the research, the ARL DSRC acquired two new platforms designed for AI workloads. The first is a clusters of four NVidia Volta servers, provided by the High Performance Computing Modernization Program. The servers feature dual socket Intel Xeon Gold 6142 processors 2 NVidia V100 GPUs per node, and 100 gigabit per second EDR InfiniBand interconnect. The second addition is a deployable, containerized supercomputer to support artificial intelligence, machine learning, and data analytics. The system, SCOUT, is an IBM platform that features 22 training nodes, each with two IBM POWER9 processors, 512 GB of system memory, 8 NVidia V100 GPUs having 32 GB of high bandwidth memory each, and 15 TB of local solid state storage. There are also 120 inference nodes with two IBM POWER9 processors, 256 GB of system memory, 4 nVidia T4 GPUs with 16GB high-bandwidth memory and 4 TB of solid state storage. This innovative supercomputing system will provide over 6 petaFLOPS of single precision performance for machine learning training and inferencing, and in excess of 1 petabyte of high performance, solid state storage for data analytics workloads. The newest ARL DSRC system was delivered in the 1st quarter of FY20 and is expected to be in production use by the 2nd quarter of FY20.

What is High Performance Computing?

The following pages contain HPC Success Stories from across DOD Services and Agencies. They represent work done by ARL researchers at any of the HPCMP DSRCs, and work done by all users at the ARL DSRC.

High performance computing, or supercomputing, is dynamic to say the least. From early vector and later massively parallel computers employing custom processors and running proprietary operating systems, to clusters of computers containing commodity processors and running an open source operating system, Linux. The drivers were mainly physics-based models, requiring a large number of the fastest possible processors and as much memory as was possible. Those requirements still exist but new ones have arisen, such as machine learning with a demand for GPUs, at least for training algorithms, and data science, working with possibly millions of files and extensive data movement. HPC architectures for the traditional and the new look very different. Other changes are also coming, such as HPC in a container for mobile or edge computing, and access to computational resources at above secret classifications.

The HPCMP uses its technology insertion process to capture ever changing DOD requirements and implement DSRC capabilities to meet those requirements. The HPCMP continually expands DREN connectivity between users and the DSRCs, provides subject matter expertise through its User Productivity Enhancement and Training (PET) initiative, and maintains high capacity repositories for user data, backup storage, and disaster recovery.

POWERING THROUGH MOORE'S LAW

Dr. Ross Adelman
Sensors and Electron Devices Directorate,
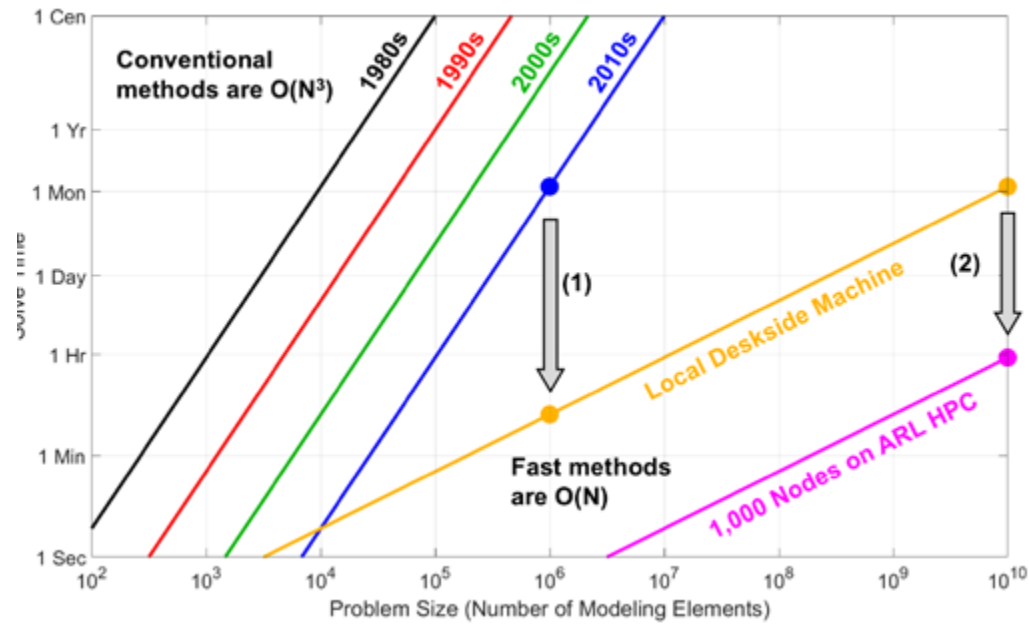Combat Capabilities Development Command Army Research Laboratory

Figure 1: While Moore's Law does provide speedups over time, it's not enough to overcome the cubic scaling of conventional methods. Fast methods and linear scaling enable problems with tens of billions of elements or more.

Project Description

The overall goal of this project is to develop fast, accurate, and scalable solvers for low-frequency electromagnetic problems. We want to solve scientific problems of interest to the Army and DOD, and use their results to inform R&D activities. Using fast algorithms and powerful hardware, our solvers can handle extremely complex problems. They run on ARL supercomputers as well as local deskside machines. We have benchmarked the solvers to demonstrate scalability, and use them every day in our research.

Relevance of Work to DOD

The Electric- and Magnetic-Field (E/H-Field) Sensing Team at the Army Research Laboratory uses computer modeling and simulation (M&S) software to explore new concepts, conduct research, and develop new technology that is beneficial to the Army and DOD. It serves as a sandbox to try new ideas, determine fundamental limits of sensor phenomenology, and test new algorithms that will run on sensor hardware. For example, we explored using the E/H-Fields generated by power lines for a variety of applications, including power-line detection, avoidance, and navigation by SUAVs, and estimating the magnitude and direction of power flow on the lines. We have also used the software to impact a DARPA program focused on very-low-frequency electromagnetic imaging. We studied the trade space between range, resolution, frequency, and noise to determine what was technically possible. Fast, accurate, and interactive M&S software enables this type of research.

Computational Approach

We use the boundary element method (BEM) in our solver. An advantage of the BEM is that they result in much smaller system matrices with fewer unknowns. However, these system matrices are dense. The problem is that conventional methods for solving these systems, such as Gaussian elimination, are slow.

The four lines in Fig. 1 show the performance of conventional methods over the last four decades. Because of Moore's law, the performance has increased substantially. However, even with these increases, conventional methods scale cubically: every time you double the size of the problem, they take eight times longer to solve. This makes solving even a moderately sized problem almost impossible. For example, solving a problem with a million elements would take over a month on today's hardware.

Using fast algorithms, such as the fast multipole method, and specialized hardware, like GPUs, we were able to reduce this month to just a few minutes. That's a 10,000x improvement (arrow (1) in Fig. 1). The linear scaling that these fast algorithms provide allows us to tackle problems much larger than ever before. Using the domain decomposition method, we were able to parallelize our solver across thousands of nodes on the ARL supercomputers (arrow (2) in Fig. 1). For example, we were able to solve a ten-billion-element problem in 2.91 hours across 1,024 nodes on Centennial.

Results

We modeled four 230-kV transmission-line circuits along a 9.9-km section of right of way northeast of Washington, DC. This section is part of a larger transmission link that runs between DC and Baltimore, MD. We simulated the E-Field generated by these four high-voltage circuits. Over 70 km^2 of terrain was modeled at 1-m resolution, resulting in a model with 157 million elements. It was solved across 32 standard-memory nodes on Centennial in 3.96 hours. Alternatively, we were able to solve the problem across 8 big-memory nodes in 12.21 hours, 16 GPU nodes in 6.92 hours, and 128 standard-memory nodes in 1.29 hours, thus demonstrating the software's ability to run on many different types of hardware configurations.

The simulation results in Fig. 2 represent what an E-Field sensor would measure if placed on the ground near the lines. The E-Field peaks at 1 kV/m inside the right of way, but decreases when farther away. The E-Field generated by the power lines highlights several interesting features along the terrain, including I-95, which runs parallel to the right of way. Also visible are the tops of trees and buildings, which act as flux concentrators, pulling the E-Field towards them.

Future

Our current research is focused on extending the maximum problem size of our solver, which is currently governed by the total amount of DRAM available. Roughly 128 GB are required for every 20 million elements. This equates to roughly 35 billion elements across all of Centennial. We have started to utilize the vast amounts of scratch space available on the HPC systems (e.g., 10.8 PB on Centennial). Preliminary results are promising, showing only a mild slowdown (<2x) due to swapping. This work will ultimately enable problems with hundreds of billions or trillions of elements, enough to model the entire Earth in detail.

Co-Investigators

David Hull, Kevin Claytor, and Hugh Chung, (CCDC ARL)
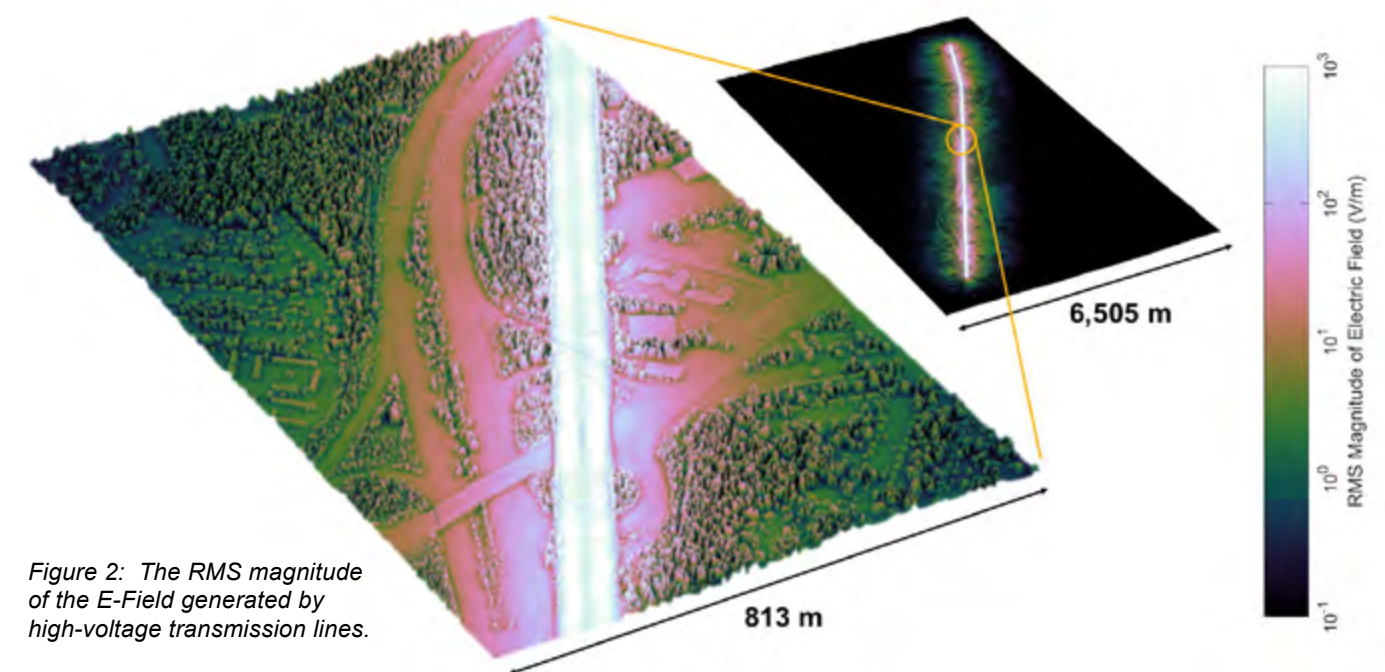Ramani Duraiswami and Nail A. Gumerov, University of Maryland, College Park

Figure 2: The RMS magnitude of the E-Field generated by high-voltage transmission lines.

HPC MODELING & SIMULATION TO SUPPORT DOD ROTOCRAFT ACQUISTION PROGRAMS

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Vehicle Technology Directorate,
Combat Capabilities Development Command Army Research Laboratory

Project Description

This project uses HPC resources to guide acquisition and digital thread systems engineering decisions for Army rotary-wing S&T programs. In particular, HPC resources are being used to perform high-fidelity aeromechanics modeling in support of the Joint Multi Role Technology Demonstrator (JMR-TD) aircraft being developed to inform the Army's Future Vertical Lift acquisition program. Four aircraft are being assessed under JMR-TD program: the Bell V280 "Valor" tiltrotor, the Sikorsky/Boeing SB>1 "Defiant" co-axial, the AVX co-axial concept, and the Karem tiltrotor concept. The first two aircraft were built and are actively undergoing test flights, while the innovative rotor technologies of the AVX and Karem aircraft are being assessed digitally through high-fidelity modeling. The HPC resources which enabled detailed studies of the AVX aircraft and tiltrotor stability are discussed here.

Relevance of Work TO DOD

The JMR-TD is one element of the Army Future Vertical Lift (FVL) priority and Cross Functional Team. Advances in vertical take-off and landing technology improve FVL vehicle capabilities and deliver improved range, speed, payload, and performance. FVL will permit Army forces to operate more effectively across wide areas while maintaining joint support. The capability to transport vehicles and equipment across operational distances will allow future forces to pose the enemy with multiple dilemmas as forces with mobility, protection, and lethality arrive at unexpected locations, bypassing enemy anti-aircraft weapons and strong points.

Computational Approach and Results

The AVX conceptual compound coaxial rotorcraft, shown in the figure below, consists of two counter rotating rotors with hubs, and fuselage (fuselage

Figure 1.
(inset left)
AVX configuration for the JMR-TD program.
(below)
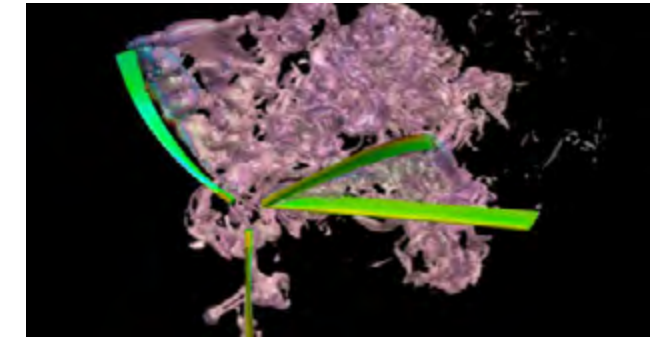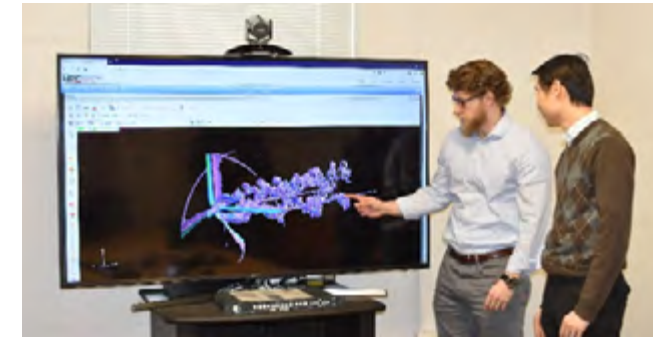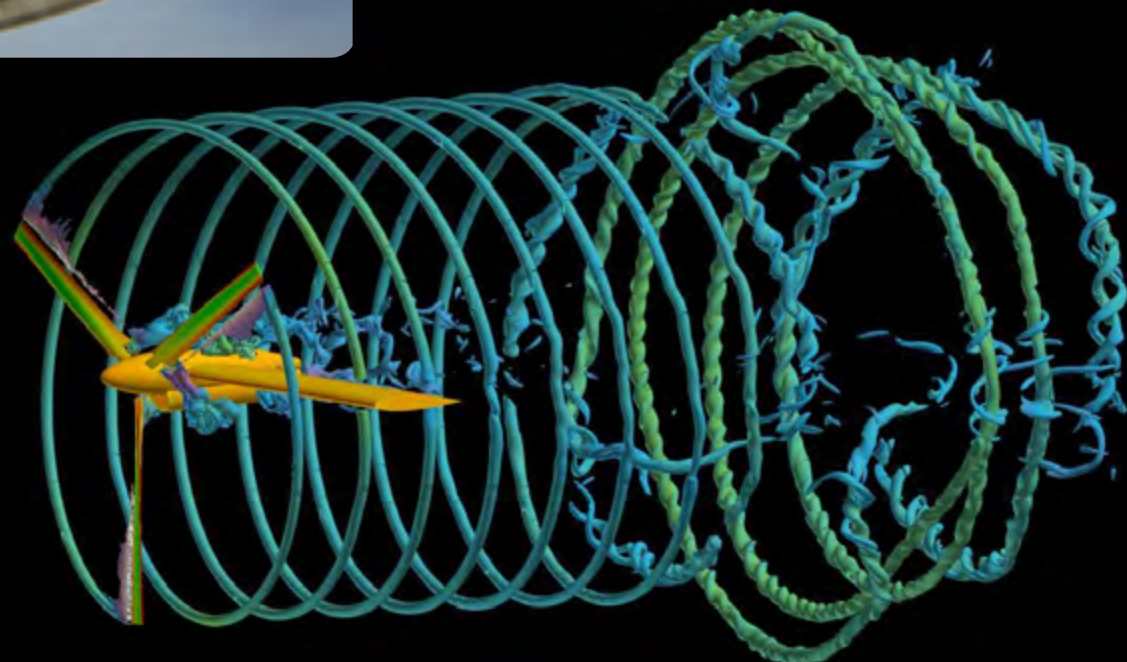Helios solution of AVX configuration in forward flight.

Figure 2.
CCDC Army Research Laboratory researchers discussing CFD/CSD simulation of semi-span XV-15.

body, canards, horizontal/vertical tails, elevators, and ducted fan shrouds). A grid system composed of 11 body-fitted unstructured grids totaling 97 million cells and an adaptive background Cartesian wake grid of 300-700 million cells provides a high-resolution description of the vehicle.

The HPCMP CREATE™-AV Helios high-fidelity rotorcraft simulation software, which couples Computational Fluid Dynamics (CFD) for the aerodynamics with Computational Structural Dynamics (CSD) for the blade aeroelasticity and trim, is used to perform calculations of the configuration on DoD High Performance Computing (HPC) systems. Each trimmed, forward-flight calculation requires about 1000 hours on 3000 cores and provides detailed analysis of the interactional aerodynamics between the coaxial rotors and between the rotors and the fuselage; as well as the resulting effects on blade deformation, stresses, and miss distance.

Prior to the availability of the Helios software and large scale HPC resources through the Frontier project, only simulations of isolated components were possible. This is one of the first fully-coupled CSD/CFD results for compound coaxial rotorcraft that includes both rotors and fuselage and enabled detailed analysis on (i) significant interference to the vorticity field, (ii) noticeable changes in the higher harmonic blade loading and stresses for the lower rotor, (iii) little change in blade loading/stresses for upper rotor, and (iv) no change in the blade miss distance. This information can be used to redesign blade structural properties or the fuselage configuration to minimize these effects. In the past, such detailed analysis was only possible through flight test.

A separate effort uses HPC resources to improve the knowledge and understanding of the whirl-flutter phenomenon to enable high-speed, reliable, and efficient tiltrotors for the FVL program. The project simulates and analyzes the XV-15 tiltrotor whirl-flutter characteristics which stem from aeroelastic coupling between the wing and rotor. The simulations also use the HPCMP CREATE™-AV Helios high-fidelity rotorcraft simulation software to perform the coupled CSD/CFD whirl-flutter calculations on DoD HPC systems.

The grid system includes four body fitted unstructured grids with approximately 15 million cells, and an adaptive Cartesian off-body grid of 30-50 million cells to provide high-resolution information about the model wake with the interactional aerodynamics between the rotor and wing. Each transient whirl-flutter simulation uses approximately 60 hours on 1000 cores and provides detailed analysis of the aeroelastic coupling between the wing and rotor. A novel signal processing methodology has also been developed to process the transient data to extract vehicle stability characteristics. This is the first full CSD/CFD whirl-flutter simulation for any tiltrotor aircraft.

Future

The full vehicle coaxial Helios model will be developed further to include a capability to use CFD aerodynamic loading from the fuselage to trim the full aircraft with the elevators. This will provide realistic trim parameters for the full aircraft simulations at high speed.

The methodology for analyzing tiltrotor whirl flutter will be further applied to analyze a new state-of-the-art TiltRotor Aeroelastic Stability Testbed, known as TRAST, being developed by Army/NASA. The TRAST wind tunnel model will be tested at the Transonic Dynamics Tunnel located at NASA Langley Research Center.

Co-Investigators

Ethan Corle, Dr. Matthew Floros, Dr. Rajneesh Singh (CCDC ARL / VTD)

LARGE SCALE SIMULATIONS OF MULTIPHASE FLOWS IN AVIATION GAS TURBINE ENGINES

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Combat Capabilities Development Command Army Research Laboratory

Project Description

This project is focused on developing massively parallel large eddy simulation tools to enable fundamental studies of highly dynamic multiphase flows, turbulence, and particle deposition in aviation gas-turbine engines. Due to the rich multiphysics nature of the internal flow dynamics, and the exceedingly wide range of scales present, large scale simulations using several 100s of millions of core-hours per year are essential to shed light on the underpinning physics. The studies conducted include investigations of liquid jets evolving in unsteady oxidizer cross flows, and complex sand-laden flows in turbine engines ingested from rotorcraft brownout. This work is sponsored by a Frontier award to ARL providing unprecedented computing power to enable truly disruptive and pioneering work in propulsion sciences.
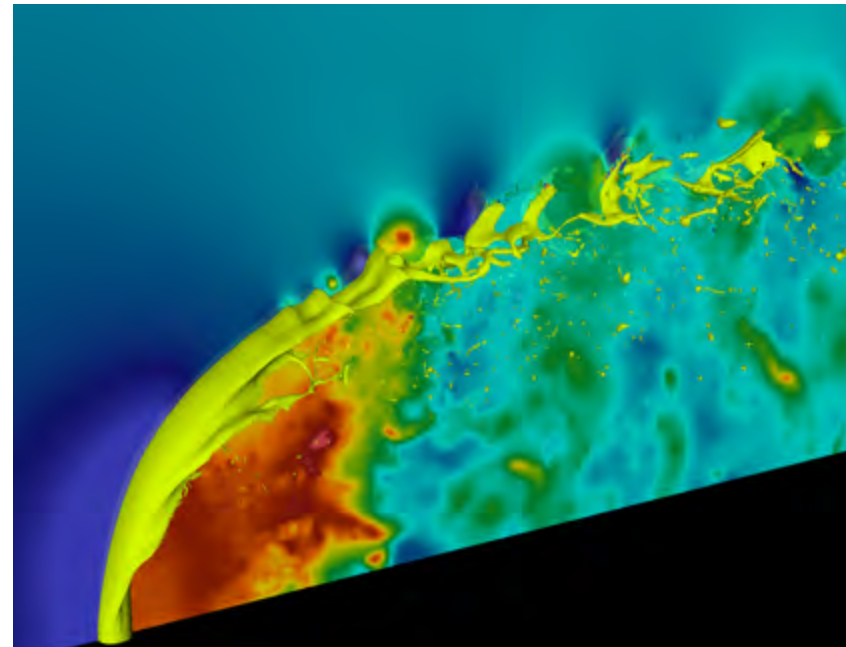

Figure 1. DNS of jet in cross flow under engine relevant conditions. Instantaneous jet isosurface and velocity magnitude contours, 400 Mil cells.

Relevance of Work to DOD

This work supports the Army Modernization priority Future Vertical Lift (FVL) by conducting fundamental research in propulsion science that is critical to developing very powerful engines with improved durability and fuel-efficiency. An important outcome is providing validated high-fidelity models to inform the Improved Turbine Engine Program requirements for Future Long-Range Assault Aircraft and Future Attack Reconnaissance Aircraft programs replacing the UH-60 Black Hawk and AH-64 Apache engines. This project also provides the fundamental knowledge to improve contemporary model tools and ultimately impact Army FVL, develop disruptive concepts in multi-domain operations for 2035+, as well as address DoD priorities in big data analytics, and hypersonics.

Computational Approach

The simulations presented here were conducted using the large eddy simulation (LES) technique to study two fundamental problems critical to engine performance, 1) primary breakup of turbulent liquid jets in cross flow, and 2) unsteady aerodynamics in a transonic power turbine sector, using HPCMP machines, Excalibur, Centennial, and Onyx. In LES the large scales of motion of turbulent flow are computed directly while small-scale motions are modeled using universal laws. This modeling approach enables the study of realistic engines by incorporating geometric features with microsecond time fidelity and sub-millimeter resolution, while generating petabytes of data. In the first case, fuel injection is simulated in a gas-turbine relevant jet in cross flow environment that precisely resolves the interface and high-shear flow interactions in the dense region. As the spray expands, the droplets are tracked in the dilute phase using a stochastic model coupled with secondary breakup and vaporization which controls the ignition process. Next, an engine turbine geometry is utilized to simulate the first stage nozzle and rotor blade rows moving at 100,000s rpm. Near the blade walls, a local equilibrium wall model is applied to compute the shear stress and reduce the cost. Combined, these simulations made use of 100-400 Mil cell resolution, and used 125 Mil core hours this year.

Results

The simulations pertaining to primary breakup in liquid jet-in-crossflow studied the role of momentum flux ratio and oxidizer temperatures at high pressures. A round jet nozzle is utilized with a diameter d_j=0.8 mm, velocity U_j = 108 m/s, Reynolds number, Re_l = 31,260, Re_g = 5,570, and oxidizer temperature, T_g=473K. Fig. 1, shows the features of jet breakup undergoing phase change using a mesh comprising of 400 Mill cell elements. The studies revealed the governing mechanism of droplet production for various operating conditions comprising of i) growth of surface instability waves due to turbulence and aerodynamic interaction followed by ii) ligament release from the liquid column due to shear, further breaking into droplets in the dilute region. The spatial distribution of the droplets and the deflection of the liquid column were found to be governed primarily by the jet momentum flux ratio. An understanding of the governing factors is of utmost importance to increase the performance of current and next generation FVL gas turbine engines.

Next, results from the unsteady aerodynamics in a transonic power turbine sector are presented. The annular geometry spans from the combustor exit to the first stage turbine. It comprises of 24/34 stator/rotor vanes with a mean chord length of 21.1 mm. At the inlet, an axial flow is specified at Mach 0.1, pressure of 2.02 MPa and temperature of 1669.78 K with Re_g = 130,392. The rotor speeds considered in our studies include the design point and multiple off-design conditions (up to 50% reduction in speed).

A highly resolved mesh consisting of 100 Mil cells is used to capture the fine scale dynamics produced from the high levels of unsteadiness and rotor dynamics, along with a wall modeling approach, see Fig. 2. This large-scale study allowed, for the first time, the calculation of aerodynamic performance of a power turbine sector in a moving rotor environment with blade resolution of y+ ~ 100 in viscous units. The results have shown that the aerodynamic performance in engines is significantly degraded when operating away from the design point. ARL is addressing these issues by developing "incident tolerant" blade designs that are enabling future variable speed power turbines. This will provide improved performance for high-speed tilt rotorcraft, where the power turbine is slowed down by as much as 51% during cruise flight.

Future

Future plans include pursuing hybrid analytic algorithms combining physics based models with machine learning framework for reduced order modeling of non-linear systems and rigorous uncertainty quantification. An in-situ visualization framework will be critical to improve data analytics for studies involving 1000's of runs. We will continue working with our technology transition partners at AvMC, NAVAIR, and AFRL, to impact DoD priorities.

Co-Investigators

Dr. Muthuvel Murugan, Dr. Anindya Ghoshal, Dr. Simon Su (CCDC ARL) Dr. Nishan Jain, Prof. Alison Flatau (University of Maryland) and Dr. Dokyun Kim, Frank Ham (Cascade Technologies)
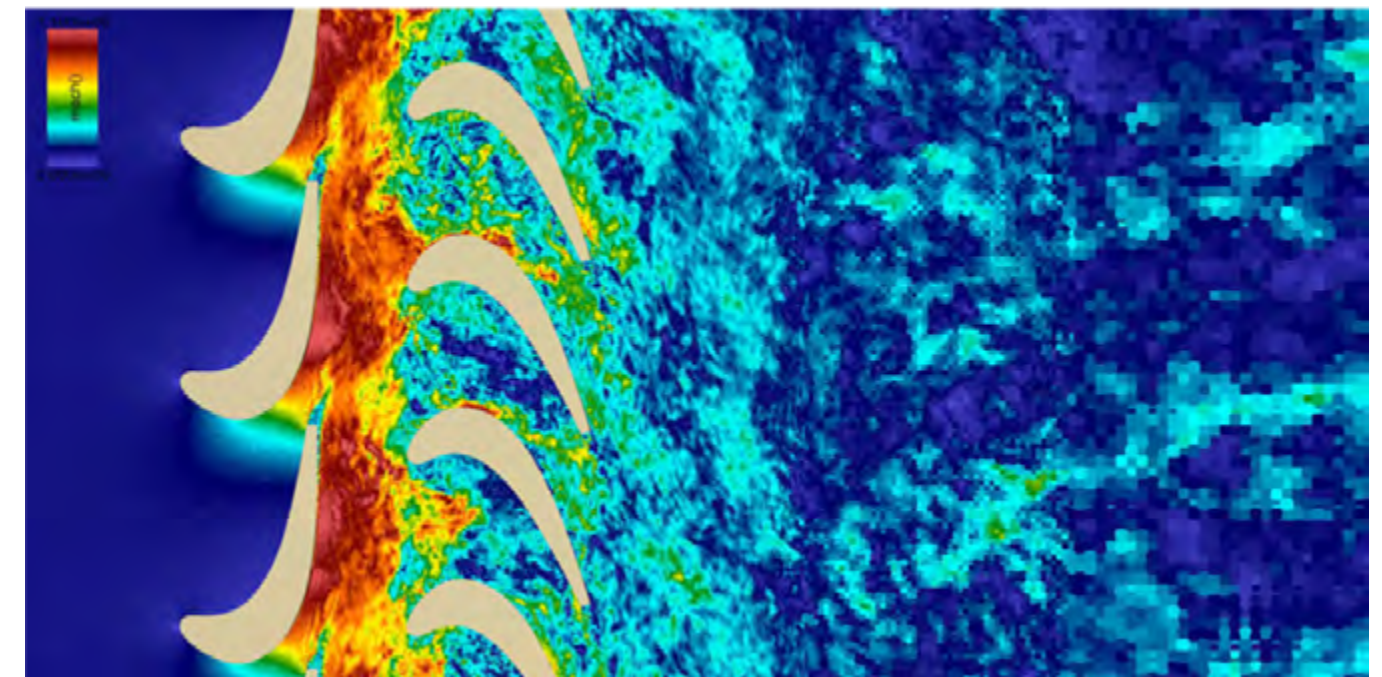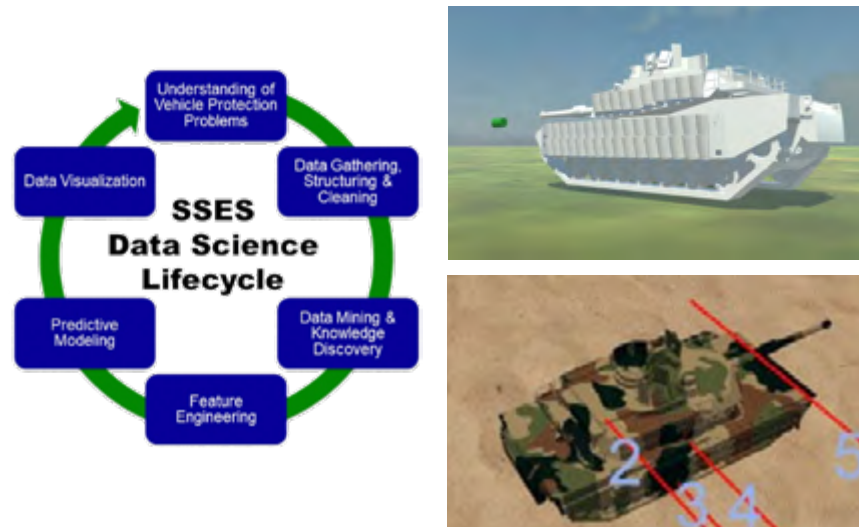

Figure 2. LES results of instantaneous Mach no. contours across the transonic turbine power stage, 100 Mil cells.

SIMULATION AND DATA SCIENCE OF VEHICLE PROTECTION SUITE

Dr. Michael Chen
Weapons and Materials Research Directorate,
Combat Capabilities Development Command Army Research Laboratory

Figure 1: (left) SSES data science lifecycle. Figure 2: (top right) Launch of a notional countermeasure from a vehicle model. Figure 3: (bottom right) Residual shot line analysis on a nonstationary vehicle.

Figure 4: Dr. Michael Chen presents an end-to-end APS event at the ARL DSRC's Visualization Lab

Project Description

Due to rapidly evolving threats on battlefields, vehicle protection subject to strategic and operational mobility requirements has been challenging. Over the past two decades, the Combat Capabilities Development Command, formerly RDECOM, has pursued computational code development of active protection systems (APS). Recently, ARL embarked on the System Survivability Engineering Software (SSES) mission program, aiming to expand simulation features of the vehicle protection suite (VPS) and develop a more scalable and sustainable software system. In addition, by leveraging high performance computing resources, SSES data science intends to uncover patterns and gain insights to an unprecedented extent. The lifecycle (Figure 1) starts with understanding of vehicle protection problems, high-level questions such as what kind of threats? how to counteract? when to respond? where to engage? and so on. Once the objectives are defined, data will be gathered, structured and cleaned for inconsistent and/or missing values. Analyses of data sets can then be conducted to identify patterns, establish relationships, and discover knowledge. With the insights to certain phenomena, imp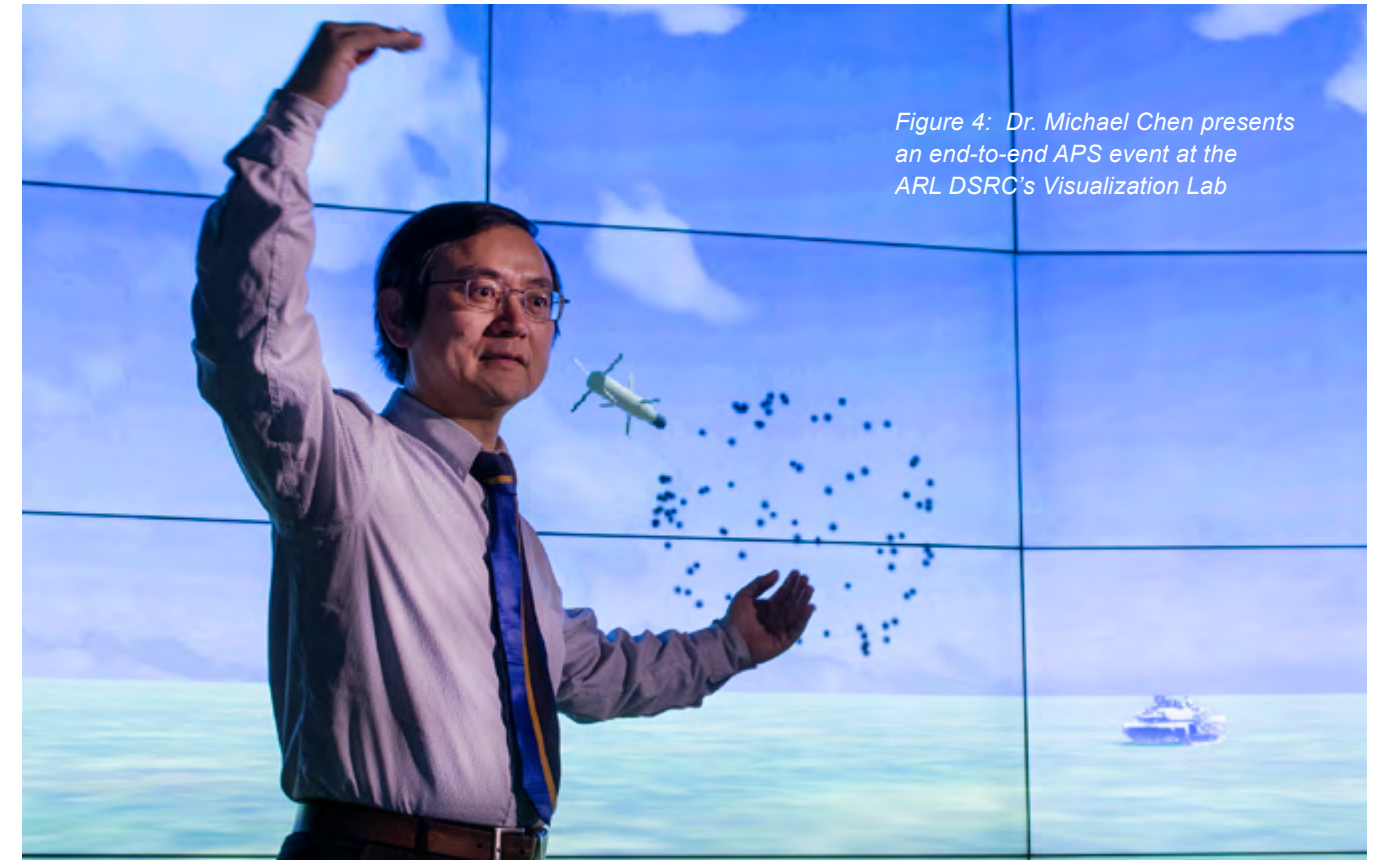ortant features will be selected to reduce noises and more meaningful models can be constructed. This process will continue by training and validating machine learning models, evaluating their performance, and using them to make predictions. At the end, results will be communicated through interactive data visualization.

Relevance of Work to DOD

The Army Futures Command has focused on the development and acquisition of next-generation combat vehicles (NGCV), one of the Army's top six modernization priorities. The VPS has been identified to be one of the enabling technologies for NGCV. In recent years, the Army has developed a suite of protection technologies for combat vehicles, which have evolved dramatically, moving beyond traditional ballistic and blast protection, and spanning into hit avoidance through the adoption of active protection, countermeasures and signature management. The objectives of this project are to assess the strength and the weakness of combing multiple protection mechanisms for combat vehicles against all applicable threats, and to provide predictive solutions that will inform the Army regarding an optimal ratio between active and passive armor types for potential reduction in vehicle size and weight.

Computational Approach

The simulations consist of three phases: pre-processing, solution optimization, and post-processing. At the beginning, we adopted an SSES input deck comprising a number of keywords for model construction, suitable for dynamic input configurations and robust parametric study. In the solution analysis and optimization phase, threat detection, identification and tracking are processed, followed by launch of a countermeasure through fire controls. It features a multi-threaded and parallel-enabled executable, suitable for complex data processing and large-scale random sampling. The post-processing leverages in-situ visualization with versatile ParaView tools, providing real-time data rendering, suitable for timely feedback, interactive model validation and survivability assessment.

Results

A typical hard-kill APS scenario begins with launch of a threat, followed by threat launch-flash signature detection by an IR warning system. Once detected, it is handed over to a radar system for threat tracking. In the meantime, gimbaled actions of the radar system and a launcher take place. The tracking data were processed through Kalman filtering and then fed into a fire control unit. Based on a desired intercept range, the fire control calculates and determines the launch time of a countermeasure. Once the countermeasure is launched (Figure 2), an onboard fuze operates at its design function and detonates the warhead under specified conditions. The warhead detonation generates a cluster of fragments, and the fly-out of the fragments is intended to damage or destroy the incoming threat. After the engagement, we conduct shot line analyses of the threat residuals to estimate hit locations and to assess potential risks to a vehicle target. A nonstationary high-fidelity tank model consisting of hundreds of thousand triangular elements was adopted (Figure 3). The end-to-end APS simulation is presented (Figure 4).

Future

Integrated survivability is an ultimate goal for protection of combat vehicles. The pursuit of the objective is enabled by the VPS modeling and simulation, which align with the concept of layered protection, combining not only hard- and soft-kill APS but also obscurant, smoke, camouflage, and decoy technologies on top of passive armors, such as explosive reactive armor. We will develop scientific methods, algorithms and data analytics techniques to extract knowledge from SSES Big Data consisting of an array of databases in threats, sensors, countermeasures, vehicles, etc. We will unify computational simulations, data mining and machine learning to achieve holistic assessment of vehicle survivability using data. Further, the concepts of autonomy and cooperative protection network for maximum survivability and minimum collateral damage in multi domain operations will be demonstrated in the long run.

Co-Investigators

Simon Su (CCDC ARL CISD), Ross Smith (PETTT), Vincent Perry and Michael An (ARL DSRC) and James Gough (University of Maryland Baltimore County)

CFD SIMULATION OF VORTEX INTERACTIONS RELEVANT TO ARMY MUNITIONS

Dr. James DeSpirito
Weapons and Materials Research Directorate,
Combat Capabilities Development Command Army Research Laboratory

Project Description

The aerial maneuverability and agility of missiles and guided-projectiles typically generate vortex-dominated flows that shed from the munition control surfaces (e.g., canard, wing, or strake) or the vehicle body itself (Figure 1). The interaction of these vortices with downstream portions of the vehicle body (e.g., tail fins) can lead to adverse aerodynamic loads that are difficult to predict to the required accuracy. At a minimum, these interactions can reduce the available control authority below the design requirement. At the extreme, the vehicle can attain a state in which the guidance, navigation and control system will have difficulty maintaining control of the vehicle. Our goal is to quantify the prediction accuracy of our high-fidelity computational fluid dynamic (CFD) tools, extend our understanding of vortex-interaction flow physics, and enhance our capability in predicting these effects.

Relevance of Work to DOD

The Army Futures Command number one modernization priority is Long-Range Precision Fires, including both missile and projectile systems. Increasing range for both strategic and tactical operational missions means the munition will likely be operating at times in the flight environment where vortex interaction effects will impact the maneuverability or control of the vehicle. The need to fully assess and improve the prediction capability of our high-fidelity computational analysis tools is of significant importance.

Computational Approach

We recently investigated the nonlinear aerodynamics experienced by a 155-mm, spin-stabilized (85 Hz) artillery projectile while flying at very high angles of attack ($\alpha \leq 40°$). Gyroscopically stabilized projectiles launched at steep angles for indirect fire experience a large yaw of repose in the subsonic regime and uncertainties are associated with the aerodynamics at these high angles of attack. Our goal was to evaluate the role of body-shed vortices on the aerodynamic loads at these flight conditions. We compared steady Reynolds-averaged Navier-Stokes (RANS) and time-accurate RANS/Large-Eddy Simulation (LES) predictions using the CREATE-AV KESTREL solver, employing the duel-mesh adaptive mesh refinement (AMR) capability. The AMR capability provided an efficient method to resolve the vortices shed from the projectile body. Mesh sizes ranged from 21 to 85 million nodes, dependent on projectile angle of attack.

Results

Above 20° vortices begin to shed from the projectile, as shown in Figure 2. These vortices are naturally asymmetric due to the spin of the projectile so they induce large side moments as the angle of attack increases. The sign of the RANS/LES yawing moment predictions changes between 28° and 32°. Figure 2 shows that this change in sign corresponds to the shifting of the shed vortex asymmetry from one side to the other.

Future

This study was the first to computationally characterize the aerodynamics of a spin-stabilized munition in this Mach regime at high angles of attack. The predicted nonlinearities in the aerodynamics provide insight needed to improve the experimental data reduction methods and improve the accuracy of both unguided and guided munitions. Future work includes comparing the induced yawing moments in a non-spinning configuration of the same projectile to isolate the effects of spin at the high angles of attack. The methods used here will also be applied to other ongoing vortex-interaction studies where AMR will reduce the computational burden of resolving the vortex structures.

Co-Investigators

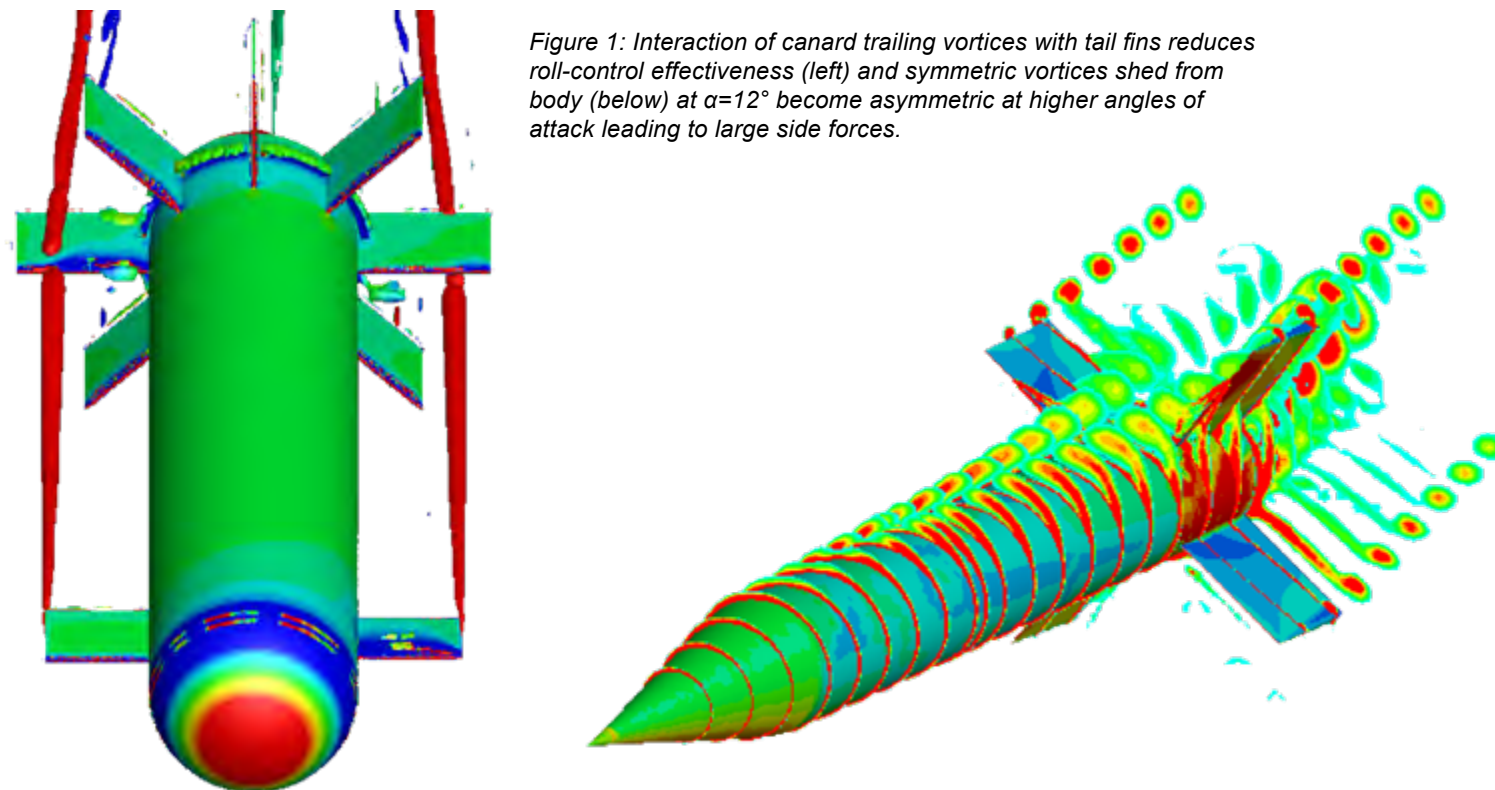Dr. Joseph D. Vasile, Dr. Sidra Silton, and Dr. Jubaraj Sahu (CCDC ARL WMRD)

Figure 1: Interaction of canard trailing vortices with tail fins reduces roll-control effectiveness (left) and symmetric vortices shed from body (below) at α=12° become asymmetric at higher angles of attack leading to large side forces.
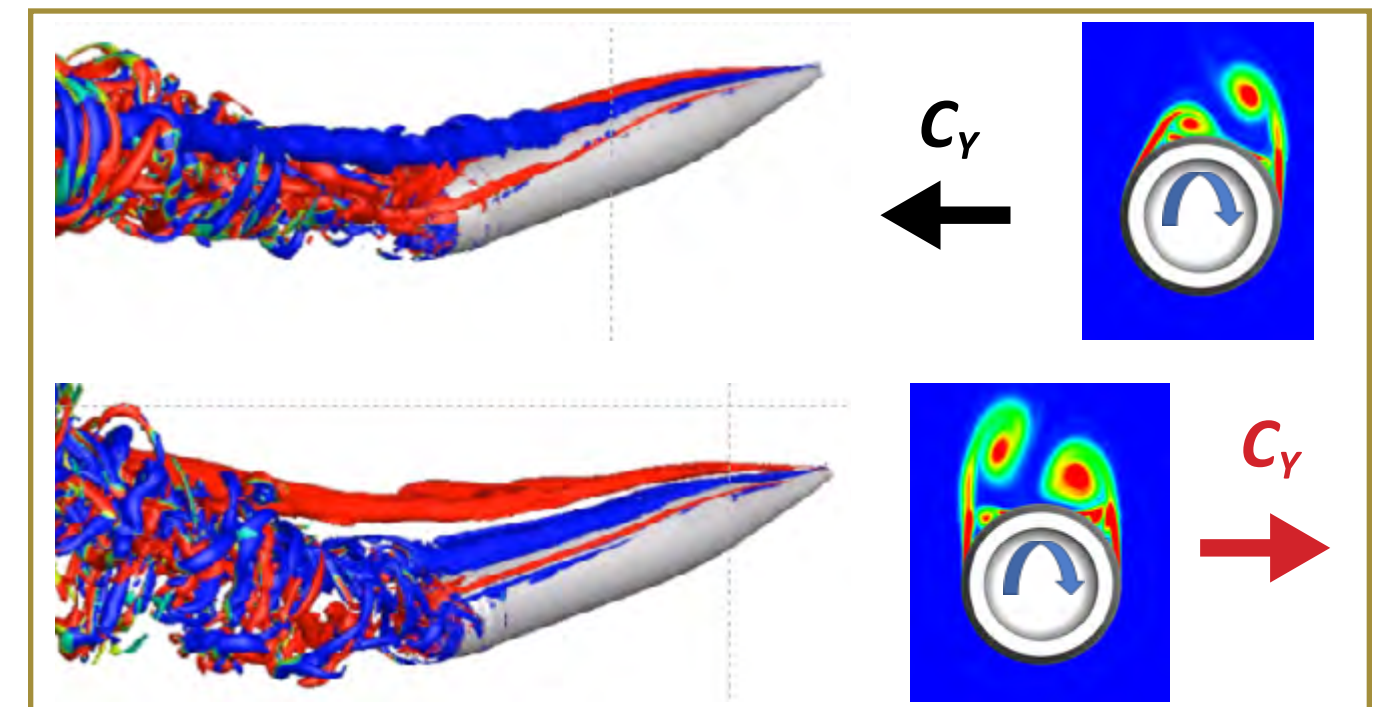

Figure 2: (Left) Isosurfaces of instantaneous, scaled Q-criterion colored by x-vorticity at Mach 0.77 and α= 28° (top) and α= 35° (bottom); (Right) Contours of instantaneous vorticity magnitude in cross-plane at 4.2 calibers from nose at corresponding α; direction of side force is indicated.

COMPUTATIONAL MODELING OF LOWER LEG ACCELERATIVE LOADING

Dr. Carolyn E. Hampton

Weapons and Materials Research Directorate,
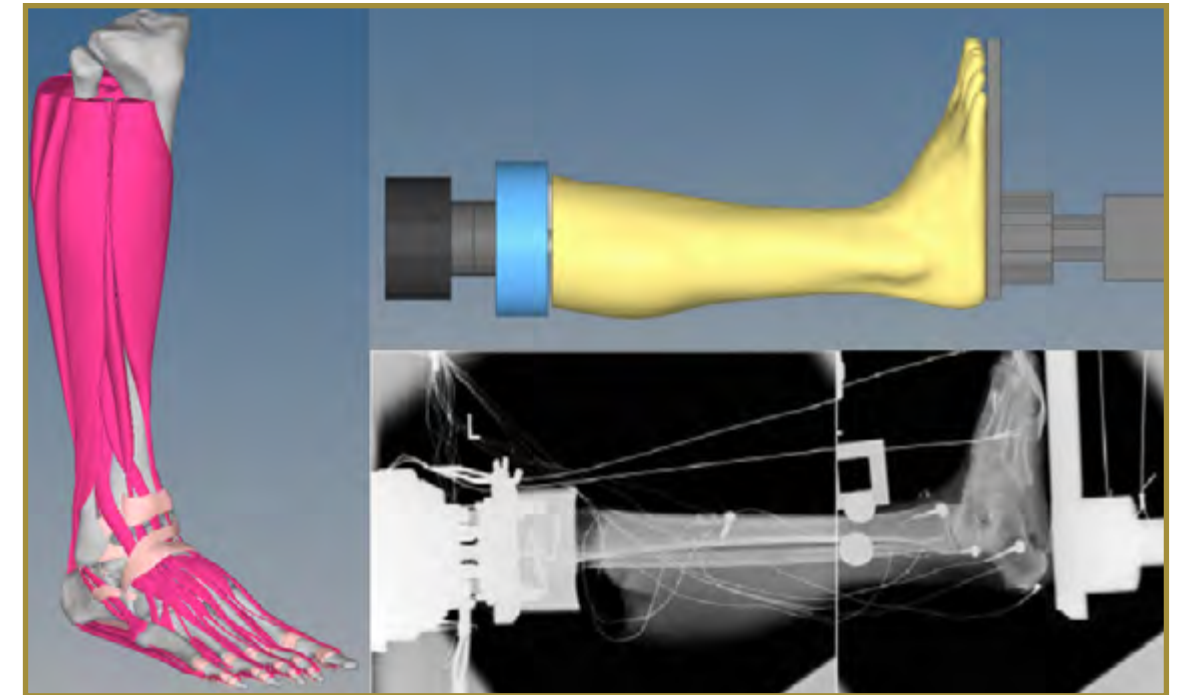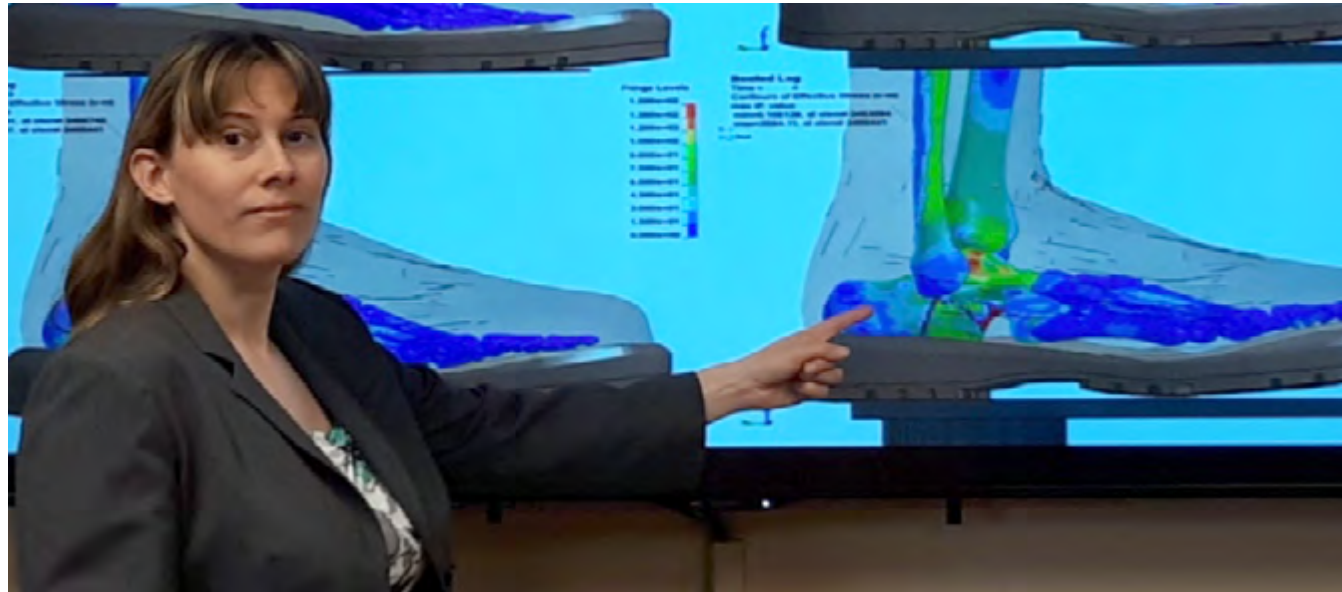Combat Capabilities Development Command Army Research Laboratory

Figure 1. Lower leg segmented 3D geometry (left) was used to generate the finite element leg model (top right) to simulate the pendulum impact experiment (bottom right).

Project Description

ARL is supporting the warfighter by researching prevention and protection technologies to maintain Soldier's lethality. Because battlefield threats are constantly changing, this requires that ARL be able to rapidly identify and respond to new challenges. Accelerative loading of the lower leg is an example of such a threat that emerged from past Army engagements. ARL researchers, in combination with a collaborating university at ARL Central, leveraged the ARL DSRC supercomputers to understand the physics leading to injury and the effectiveness of current protective footwear. This project both addresses the accelerative loading injuries and serves as a template to evaluate the mechanics of and protections against novel emerging threats.

Relevance of Work to DOD

Lower extremity fractures make up 18.5% of musculoskeletal injuries in deployed service members. The majority of injuries are caused by detonated explosive devices under vehicles resulting in accelerative loading though the vehicle floor. These injuries reduce Soldier combat readiness and mobility and also lead to disability and reduced quality of life after service. Computational simulation provides methods to understand the mechanics causing lower extremity injuries and evaluate the effectiveness of armors and injury prevention devices

Computational Approach

A human body finite element model was developed from commercially available human body geometric data. The lower right leg of this model (Figure 1) includes the long bones (tibia and fibula), ankle and heel bones (talus and calcaneus), and the small tarsal bones of the foot. The 3D bones and homogenized soft tissue volumes were meshed with 2.5 million tetrahedron elements and assigned material properties from the literature.

The initial finite element model was validated by comparing axial force transmission in cadaveric lower leg pendulum impacts. This experimental setup approximates the accelerative loading from the vehicle floor in underbody blasts. Following, the lower leg finite element model was combined with a combat boot model to evaluate the peak force mitigation offered by footwear. The modeling approach also allows for non-invasive measurement of localized stress concentrations indicating injury-prone regions.

All finite element models were simulated with the LS-DYNA finite element solver on the Cray XC40 Excalibur cluster in the ARL DSRC. Each simulation runs on 32-64 cores and requires 5-10 hours to simulate 20 ms of a lower leg impact. By running jobs in parallel, entire test suites containing dozens of simulations can be run in one day.

Results

The lower leg finite element simulations were able to reproduce the force transmitted through the leg in barefoot and booted pendulum impacts (Figure 2). The soft foams in the combat boot soles protected the lower leg by reducing the peak force, a key predictor of fracture risk, by 35%. Injuries were likely to occur when stress concentrations formed in the foot and ankle. These same areas are prone to fractures in retrospective studies of battlefield injuries. Models with stress-based fracture thresholds could predict realistic minimum impact velocities needed for calcaneus fracture.

Future

The finite element approach here used body geometry for an average person. Recent advances in scaling and posturing techniques will enable the development of personalized human body models with more natural positioning. The lower leg model can also be used to evaluate other threats, as well as existing and prototype protective equipment. Furthermore, advances in cluster resources and remote video rendering will support the additional computational costs needed to differentiate the soft tissues into individual muscles and ligaments and use more complex material models.

Co-Investigators

ARL: Michael Kleinberger, and P. Justin McKee
ARL Central & Medical College of Wisconsin:
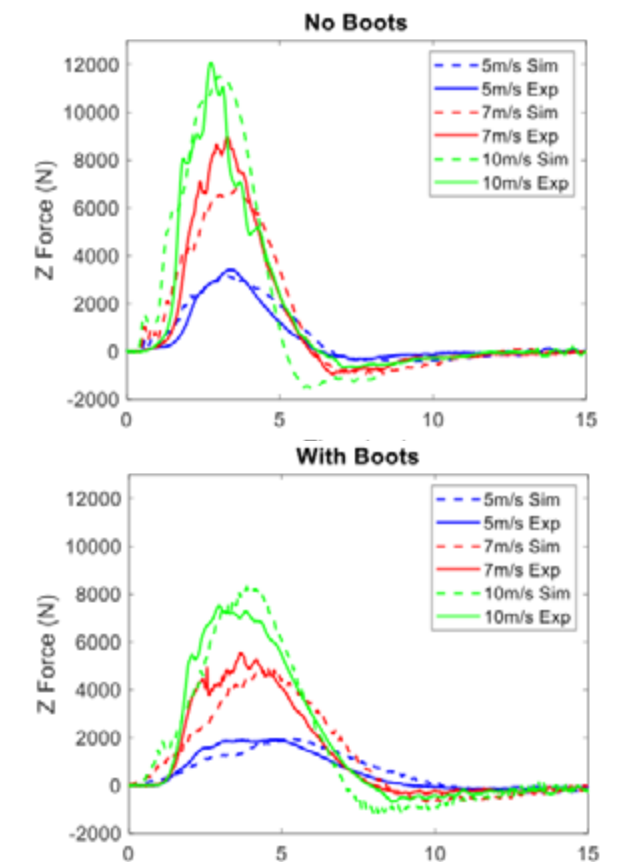Frank Pintar, Sajal Chirvi, and Jared Koser

Figure 2. Comparison of above-leg force-time response for barefoot (top) and booted (bottom) foot finite element models and experiments.

HIGH PERFORMANCE COMPUTING FOR LETHALITY & SURVIVABILTIY ANALYSIS

Douglas Howle
Combat Capabilities Development Command Data Analysis Center

Project Description

For the Army to maintain overmatch against potential adversaries, it must first understand materiel capabilities and limitations – especially with regard to survivability and lethality. Results of analysis and testing provide a strong foundation for understanding capabilities and limitations; however, testing has limitations, such as the number or type of measurements that can be obtained, the cost of planning and execution, and the ability to control test conditions. It is for these reasons that analysis – and particularly modeling and simulation – plays a vital role in defense acquisition programs.
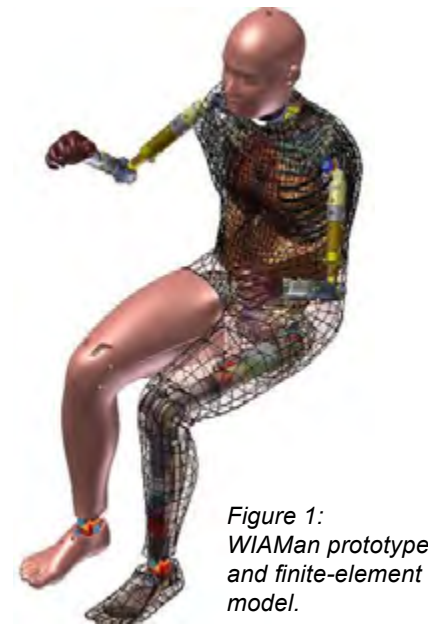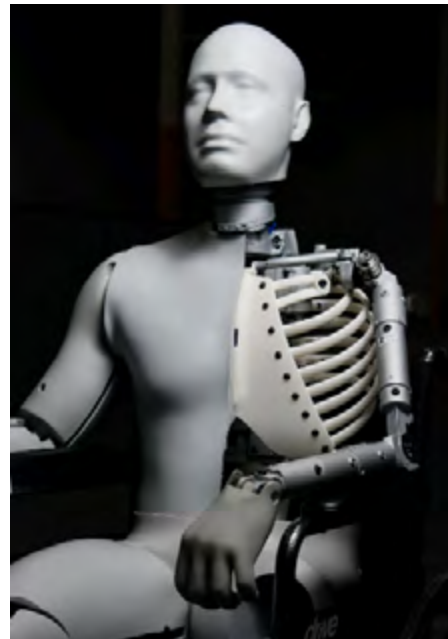
The purpose of the ballistic survivability/lethality project is to use high performance computing resources to develop accurate models and perform credible simulations which develop data needed by leaders of Army modernization and development programs. The analytical products generated under this project are used to develop recommendations for the planning of live-fire test and evaluation programs, the development of instrumentation and injury criteria and to provide insight to commanders regarding the protection afforded by specific ground vehicles to relevant ballistic and under-body blast threats

Relevance of Work to DOD

The ultimate goal of the project is to benefit the soldier by providing decision makers in the DOD with analysis results and recommendations which produce more survivable ground vehicles and increase weapons systems lethality. Previous and current customers include the following programs and offices: Joint Light Tactical Vehicle (JLTV), M1A2 SEPv3 Abrams, Bradley Infantry Fighting Vehicle, M109 Family of Vehicles, Armored Multi-Purpose Vehicle, Joint Technical Coordinating Group for Munitions Effectiveness, Warrior Injury Assessment Manikin (WIAMan), and Next Generation Squad Weapon Technology.

Figure 1: WIAMan prototype and finite-element model.

The Combat Capabilities Development Command Data & Analysis Center (D&AC) contributions to these programs include vulnerability reduction recommendations, lethality assessments, and data for the purpose of generating acquisition program requirements. Two of the six Army modernization priorities – Next Generation Combat Vehicles and Soldier Lethality – are supported by the accomplishments of this project.

Computational Approach

Many methodologies or tools were exercised on the US Army Research Laboratory's classified and unclassified high-performance computers (HPCs). As part of the Under-body Blast Methodology (UBM) for Test and Evaluation project, a modular process was developed which breaks down the complex problem of simulating buried blast effects on vehicles and occupants into several parts which can be addressed by a variety of models. Specific parts of the process – including vehicle interaction with, and response to the blast, as well as the response of occupant surrogates – are typically analyzed using highly-detailed finite-element models. The models are solved using parallel versions of software available on the HPCs. To date, computational models for common automotive-based crash test dummies and the new, more biofidelic defense-based
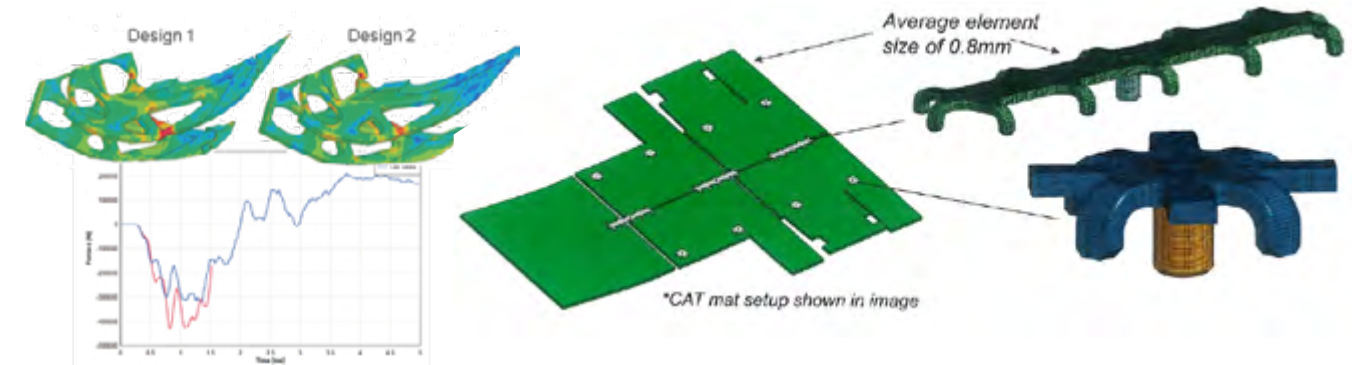

Figure 2: Sample product-assessment of vendor design alternatives and protection technologies.

test dummy known as WIAMan have been developed and validated under this project.

Other models utilized as part of this project take advantage of high performance computing to perform analyses that would not be possible on standard computing platforms. To complete a typical data package for a ballistic vulnerability/ lethality assessment for 1 ground mobile system versus 62 threats, an analyst executed 755 model runs. To complete a data package for an expedient weaponeering tool for 2 small precision munitions against 2 ground mobile targets, over 3,000 simulations were conducted on the HPC. These simulations could not be completed in a timely manner on a standard desktop computer.

Results

During the engineering and manufacturing development (EMD) phase of the JLTV acquisition program, DAC engineers performed test planning analyses to determine the most stressing conditions under which to test the vehicles. All three potential JLTV vendor designs were assessed. Ultimately the recommendations of D&AC engineers for how to test the vehicles were accepted by the Director, Operational Test and Evaluation, US Army Evaluation Center (AEC), Institute for Defense Analysis, and Program Manager JLTV. During the production and deployment phase of the JLTV program, pre-test and post-test simulations were performed and model-to-test comparisons completed in order to build a strong argument for accreditation of UBM for T&E by the Army Test and Evaluation Command (ATEC). Once the argument for accreditation was completed, a broader vulnerability analysis of two JLTV variants was completed and provided to AEC for inclusion to their evaluation of the JLTV vulnerability to occupant injury from under-body blast. The results of the broader vulnerability analysis will be used to inform commanders of the limitations of the JLTV when deciding when and where to use the vehicle in particular missions.

To estimate the return on investment afforded by using high performance computing resources, assume the cost of a test event is $75,000, the cost of a JLTV is $220,000 and three under-body blast tests can be completed on one vehicle, yielding a savings of approximately $840,000. Modeling and simulation of the same six test events would cost approximately $50,000. This cost savings does not include the cost of developing the models and performing verification and validation.

Engineers from the DAC have used physics-based tools to assess the designs of smaller vehicle components. In contrast to the large vehicle and occupant models used to assess JLTV, many of the models shown provide engineering data such as stress, strain and deflection which can be used revise components used other defense related applications.

Future

The capabilities of the ballistic survivability/lethality HPC project will continue to evolve to meet the Army modernization priorities of next generation combat vehicles, soldier lethality and long range precision fires through the development of analysis methodology and models. For example, the development of injury criteria with a highly detailed computer model of the WIAMan anthropomorphic test device is ongoing. Methodology for the assessment of blast compartmentalization technologies is planned. Tools and methodologies will be developed to support other Army modernization efforts such as future vertical lift.

Co-Investigators

Raquel Ciappi, Craig Barker, Matthew Schulz, Virginia Williams, Richard Fan, Gregory Mannix, Matthew Fox.

OPERATIONAL WEATHER FORECASTING SYSTEM FOR U.S. ARMY TESTING

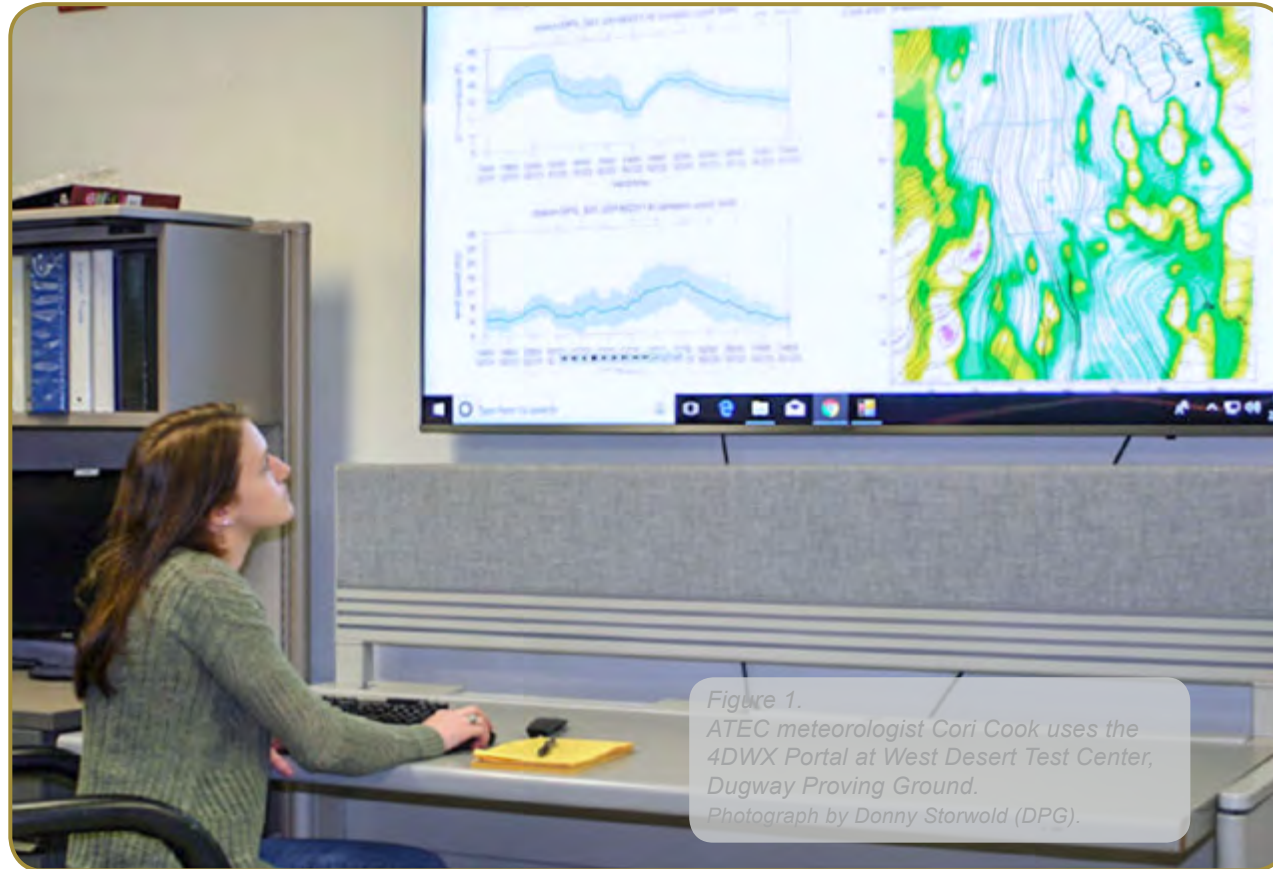*Dr. Jason C. Knievel*
National Center for Atmospheric Research

*Figure 1.
ATEC meteorologist Cori Cook uses the 4DWX Portal at West Desert Test Center, Dugway Proving Ground.
Photograph by Donny Storwold (DPG).*

Project Description

In 2017, Excalibur at the Army Research Laboratory (ARL) DOD Supercomputing Resource Center (DSRC) and Gordon at the Navy Stennis Space Center DSRC began hosting real-time execution of the Four-Dimensional Weather System (4DWX). 4DWX is advanced numerical weather prediction (NWP) software that has been a mainstay of meteorologists at the U.S. Army Test and Evaluation Command (ATEC) for roughly two decades. Executing 4DWX on DSRC HPCs rather than on dedicated clusters enables more effective, reliable use of DOD resources for Army testing, guarantees that hardware and software are current and well supported, and permits developers to more rapidly deploy computationally demanding upgrades to the software.

Relevance of Work to DOD

4DWX operations fall under the purview of the ATEC Meteorology Program, which is charged with ensuring that meteorologists at Army test facilities are equipped with the technology and expertise required to produce weather analyses and forecasts at the scales, and with the accuracy and utility, necessary for safe and cost-effective testing. Currently 4DWX is used at eight permanent Army test locations and for other temporary testing operations (often called safaris) throughout the world.

Computational Approach

4DWX was developed for ATEC by the National Center for Atmospheric Research (NCAR). The NWP core of 4DWX is the Weather Research and Forecasting Model, which like other NWP models is based on discrete approximations of continuous mathematical equations that describe the atmosphere. Four-dimensional data assimilation is used to adjust the model toward observed conditions during the analysis stage. 4DWX runs around the clock. New cycles of 1–120 h forecasts are launched via a time-based job scheduler every three or six hours, based on a test location's needs. The grid interval of the finest domains is 1.1 km. Initial- and boundary conditions are drawn from global NWP data pulled from the National Centers for Environmental Prediction. The HPCs pull local and national observations, including water surface temperatures provided by the National Aeronautics and Space Administration. For each forecast hour, large data files and hundreds of thousands of images are generated and transferred via remote synchronization to the ATEC test locations. Products are displayed through a web-based 4DWX Portal (Figs. 1 and 2). The Defense Research and Engineering Network sponsored by HPCMP is instrumental in delivering products with high availability and timeliness. Executing 4DWX in real-time at the DSRCs depends on Dedicated Support Partitions (DSPs) that the HPCMP makes available.

Results

The project demonstrates the feasibility and utility of using shared resources at the DSRCs for operational weather forecasting in support of the ATEC Meteorology Program. Since 2017 when redundant real-time runs began on Excalibur and Gordon, availability of 4DWX forecasts has been >99.7%, an extraordinary level of reliability.

Future

Future plans for the DSRC HPCs include large-eddy simulations with FastEddy, a GPU-based model newly developed by NCAR that will deliver weather guidance at unprecedented scales; and the ensemble version of 4DWX, which provides information about the uncertainty inherent in all NWP models and all observations, is more skillful than individual model forecasts, and allows forecasts to be framed as probabilities.

Co-Investigators

Scott F. Halvorson (ATEC/DPG); Justin S. Shaw, Henry H. Fisher, Rong-Shyang Sheu, Yubao Liu, Scott P. Swerdlin (NCAR); Kendra M. Raab (ATEC)

*Figure 2.
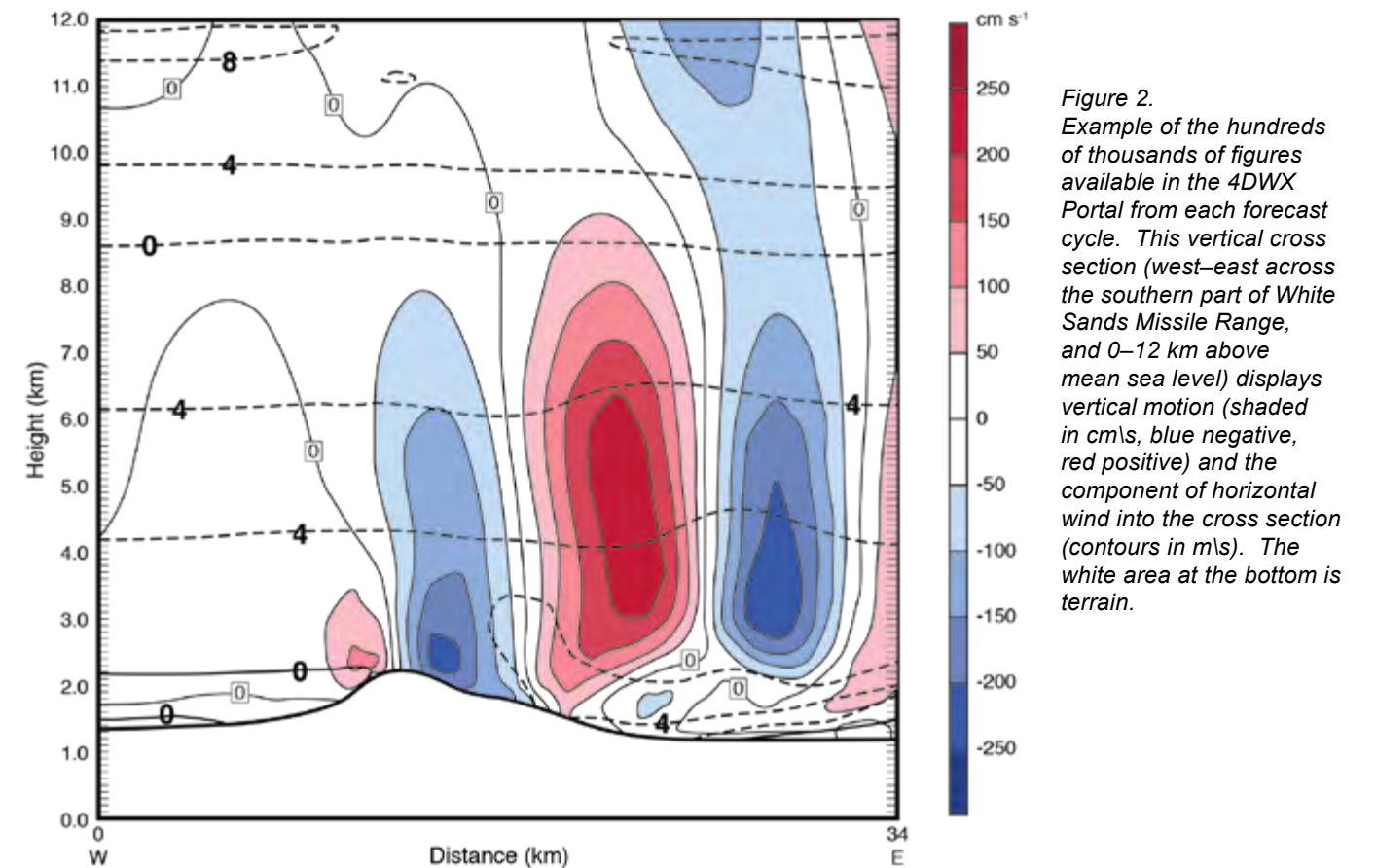Example of the hundreds of thousands of figures available in the 4DWX Portal from each forecast cycle. This vertical cross section (west–east across the southern part of White Sands Missile Range, and 0–12 km above mean sea level) displays vertical motion (shaded in cm\s, blue negative, red positive) and the component of horizontal wind into the cross section (contours in m\s). The white area at the bottom is terrain.*

IMPROVING GROUND MOBILITY PREDICTION WITH UNCERTAINTY QUANTIFICATION

Dr. David A. Lamb
Combat Capabilities Development Command Ground Vehicle Systems Center

Project Description

For decades, the U.S. Army, and our partner military organizations in NATO, have been using the NATO Reference Mobility Model (NRMM) for predicting the ground mobility of military vehicles. This was developed back in the 1970s and 1980s to cover many classes of vehicles that were common in fleets at that time, including the M1 Abrams tank, the M2 Bradley Fighting Vehicle, and the HMMWV. It used what was, at that time, cutting edge modeling techniques. Of course, things tend to age, and most things don't improve with age. In addition to modeling techniques becoming more advanced over the decades since NRMM was developed, militaries now use vehicles in classes that were never covered by the original predictions of NRMM. Some of these new classes are significantly heavier or significantly lighter than previous vehicles, and weight really matters when it comes to mobility over soft soil.

Relevance of Work to DOD

Extrapolation of NRMM to these new weights is problematic, and not as accurate as required. NRMM was overdue for an update, and projects at the U.S. Army Combat Capabilities Development Command (CCDC) Ground Vehicle Systems Center (GVSC) are looking at a "Next Generation" NRMM, or NG-NRMM. Among the other things that need to be modernized is the issue of Uncertainty Quantification (UQ). UQ wasn't really considered when NRMM was developed decades ago. More recently, however, it has become standard to include UQ in most engineering assessments, and a tool used by analysts that does not incorporate UQ is not seen as cutting edge.

Computational Approach

Clearly, to modernize NRMM, there must be a way to bring UQ into the assessment process made by the NG-NRMM. But considering stochastic uncertainties often becomes a problem of doing a Monte Carlo simulation. Fortunately, with High Performance Computing (HPC), this is achievable on scales that would have astounded the developers of NRMM back in the 70s and 80s.

An estimation of uncertainty using Monte Carlo is primarily just making a very large number of runs that are just perturbations of a common base run, to account for the stochastics. This process is in the form that is often termed "embarrassingly parallel," meaning it is parallelizable by the simple expedient of putting each of the perturbations onto its own set of processors to run many different perturbations in parallel. Of course, this oversimplifies the task, as the real work comes from understanding what perturbations are important and insuring that those are considered. However, when it comes to generating the UQ, the Monte Carlo process is critical.

HPC is very well suited to this Monte Carlo process. But there needs to be more to get NG-NRMM to work. At GVSC, we are also bringing the latest modeling techniques for soft soil and the interaction of tire and track with the ground, to enhance the fidelity of the method. The original NRMM used heuristic methods for this, but we now have physics-based models available. By bringing these physics-based models of vehicle terrain interaction (VTI), and modern methods for building surrogate models, we can get better fidelity that was achieved heuristically by NRMM. This also enables moving into vehicle classes that were not covered by NRMM, and keeps open possibilities to add more vehicle classes as needed in the future.
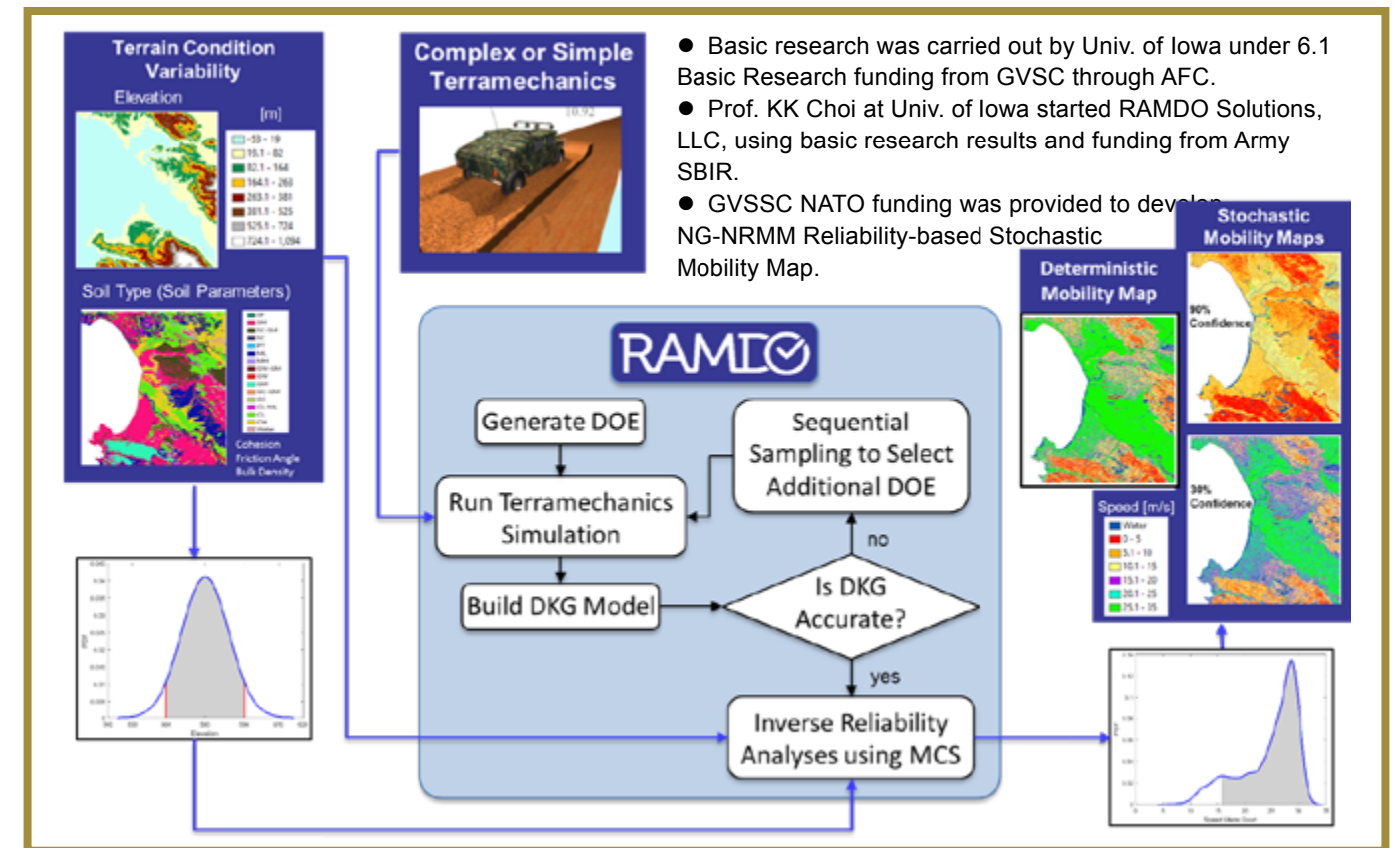
● Basic research was carried out by Univ. of Iowa under 6.1 Basic Research funding from GVSC through AFC.
● Prof. KK Choi at Univ. of Iowa started RAMDO Solutions, LLC, using basic research results and funding from Army SBIR.
● GVSSC NATO funding was provided to develop NG-NRMM Reliability-based Stochastic Mobility Map.

Figure 1: UQ Stochastic Mobility Framework

Results

So, GVSC is using the HPC system to build up NG-NRMM with physics-based models of VTI, modern surrogate model methods, and bringing UQ into the tool to enable an assessment of ground mobility that includes a confidence level for the final result. The process used is to first calculate mobility levels on representative terrain patches using high-fidelity physic-based modeling and simulation, and then build maps of battlefields by piecing together the various terrain patches to stitch a full terrain. Once the terrain is assembled, a surrogate model can be made to ease the computational burden. Then, after adding in the needed degrees of freedom for stochastic perturbation, a Monte Carlo simulation can be run to capture the uncertainty of the mobility assessment. Finally, a mobility map can be produced with confidence levels associated to each prediction.

Typically, NRMM has been used to produce what are called Go-No Go maps (G/NG), which show whether the vehicle could reach certain parts of the battlefield, and also Speed Made Good (SMG) maps to determine if the vehicle can achieve the required travel times.

Using the UQ methods empowered by the HPC resources, these G/NG and SMG maps are higher fidelity, more accurate, more flexible to additional vehicle classes, and include confidence assessments. This is a major improvement for NG-NRMM, and for the U.S. Army and all our allied military partners in NATO.

Future

The Next Generation NATO Reference Mobility Model (NG-NRMM) is going to be developed further, and will be a significant advancement on the previous NRMM. A critical part of this advance is the addition of uncertainty quantification. However, to be most useful to field commanders planning routes and maneuvers, the UQ must be applied in more ways that discussed here. We intend to apply UQ methods to more parts of the mobility problem, to the vehicles and the weather, for example. This will give the commanders access to better information for planning. The use of HPC resources will be essential to performing this UQ analysis.

Co-Investigators

K.K. Choi: (University of Iowa), Nick Gaul: (RAMDO Solutions), Tamer Wasfy: (Advanced Science & Automation Corp), Paramsothy Jayakumar and David Gorsich: (CCDC GVSC)

ENABLING SIMULATIONS OF ENERGETIC MATERIALS WITH COMPLEX MICROSTRUCTURE

James P. Larentzos
Weapons and Materials Research Directorate,
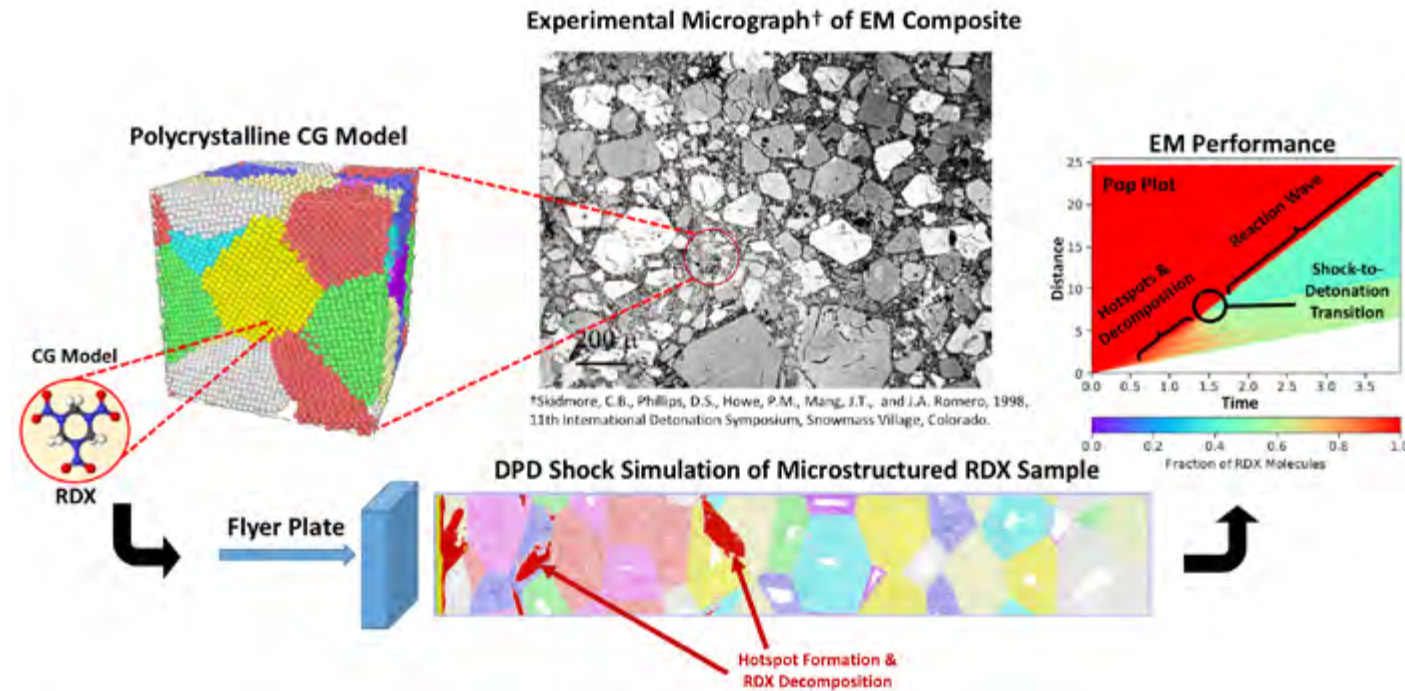Combat Capabilities Development Command Army Research Laboratory

Figure 1.
Schematic of DPD simulation of a shock front propagating through a micron-sized, polycrystalline EM sample comprised of over 1 billion RDX molecules.

Project Description

To increase the Army's readiness and maintain its competitive advantage against emerging threats, the development of a Long-Range Precision Fires capability that maintains US Army dominance in range, munitions and target acquisition is a top priority. Key to this capability development is the design and discovery of novel energetic materials (EMs) with improved performance characteristics. Accelerating the discovery of novel EMs requires the marriage of experimentation with modeling and simulation (M&S). To this end, our group is focused on the development of a multi-scale M&S framework that provides a predictive capability of EM response and performance, ultimately leading to faster, safer, less costly design of advanced EMs with increased energy output and decreased sensitivity to initiation.

EMs are comprised of complex microstructures, either as a result of processing or by design, such as in additive manufacturing. The microstructural heterogeneities present within the sample, e.g., voids, inclusions, defects in and between grains, or composition variability, such as mixtures, additives and fillers, are believed to control initiation and energy propagation in EM composites subjected to mechanical or thermal loading.
A primary objective of EM M&S is to describe the various dynamic processes, properties and mechanisms leading to initiation, deflagration and detonation using models that have reduced reliance on experimentation.

Relevance of Work to DOD

The multiscale M&S capabilities developed through ARL's Multiscale Response of Energetic Materials program enables calculations of unprecedentedly large simulations to be conducted on DoD supercomputing resources, ultimately reducing the overall time-to-solution in understanding the role of material microstructure on EM performance and leading to the accelerated discovery of new materials with extended range and greater explosive/blast effects for overmatch of future adversaries.

Computational Approach

Modeling and simulation of materials with complex microstructures is a grand challenge, where until now, an inherent gap in computational capabilities has existed in modeling grain-scale effects at the microscale, precluding such effects in macroscale models. Our group has previously developed novel coarse-grain (CG) techniques that treat chemical reactivity, enabling a critical advance in capability for modeling the multiscale nature of the energy release and propagation mechanisms in advanced EMs. Innovative algorithm developments rooted within the dissipative particle dynamics (DPD) framework have enabled extensions in both the length and time scales far beyond those ever realized through atomistic-based simulations.

In collaboration with Sandia National Laboratory, we have transitioned these DPD capabilities into the widely used LAMMPS software, the premier software for particle-based simulations. With our highly-optimized DPD-LAMMPS software running on DSRC supercomputers, we are now able to perform unparalleled explorations in EM research. We have demonstrated these advances in simulation capability by modeling a shock front propagating through a micron-sized, microstructured EM sample of the conventional explosive RDX (see Figure 1). For system sizes exceeding 1 billion particles, the time-to-solution for the CG model is the order of hours, whereas the only viable alternative (a fully-atomistic model) requires the order of years using modern, dedicated supercomputing resources.

Results

Microstructural heterogeneities in the RDX samples are modeled by creating geometries either containing porosity or comprised of polycrystals. The simulations subject the RDX samples to shock conditions, where a flyer-plate impacts the surface of the material. This generates a compressive shockwave that interacts with multiple defects (e.g., voids, grain boundaries, etc.) as well as secondary shockwaves generated from those defects, transferring energy to surrounding particles, and locally initiating chemical reactions. Initial hot-spot formation and the extent of chemical reactivity depends upon a number of factors, including the average grain-size and/or pore-size distribution and the speed, shape and character of the shock front through the sample.

Future

To assess the macroscale response, these capabilities are currently being transitioned to the Hierarchical Multiscale Simulation (HMS) Cross-Cutting program supported by the ARL Enterprise for Multiscale Research of Materials and the HPCMP's "Terminal Ballistics for Lethality and Protection Sciences" Frontier project, providing a means of directly coupling the particle level description of the EM to continuum level predictions at the macroscale. The coupled DPD-HMS approach requires many thousands of simultaneous DPD simulations, which can only be achieved with the highly-scalable, highly-optimized DPD-LAMMPS software pioneered by our group. Without the reduction in the time-to-solution presented here, such multiscale approaches would not be tractable. These DPD-HMS predictions will directly translate to efforts in cost-efficient and expedient design of microstructure-dependent material systems.

Co-Investigators

John Brennan, Sergey Izvekov, Betsy Rice, Brian Barnes, Jarek Knap, Ken Leiter
and Rich Becker (CCDC ARL) Timothy Mattox and Christopher Stone (HPCMP PETTT)
Aidan Thompson, Steve Plimpton, Stan Moore and Daniel Ibanez (Sandia National Laboratory)
Martin Lísal (Institute of Chemical Process Fundamentals of the Czech Academy of Sciences, Czech Republic)

FINITE-ELEMENT MODELING OF TEXTILES FOR BURIED BLAST EXTREMITY PROTECTION

P Justin McKee
Weapons and Materials Research Directorate,
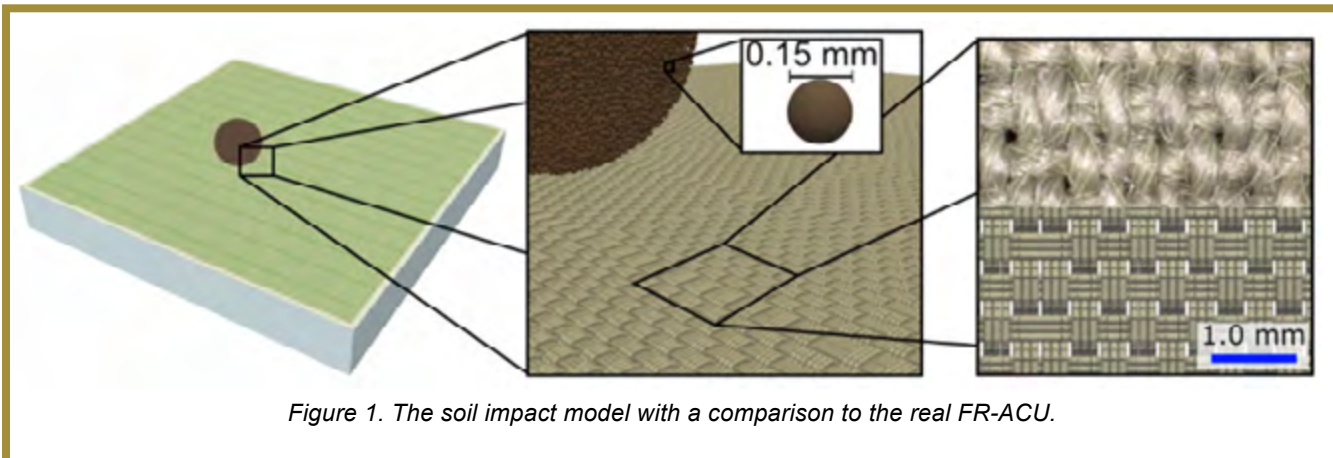Combat Capabilities Development Command Army Research Laboratory

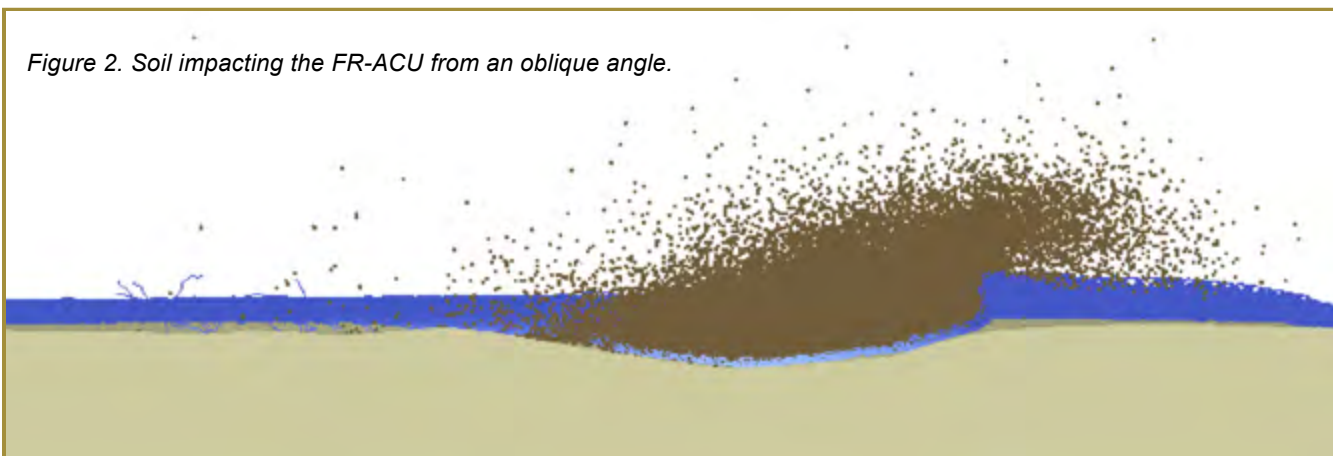*Figure 1. The soil impact model with a comparison to the real FR-ACU.*

Figure 2. Soil impacting the FR-ACU from an oblique angle.

Project Description

Soil propelled by buried blasts can cause extensive soft tissue injury to the extremities that is difficult to treat and can lead to long term complications and health care costs. The Soldier's uniform is the only protection that covers much of the extremities, where the need for mobility restricts applicable armor. Our approach is to optimize textiles in garments worn over the extremities. A finite element (FE) modeling approach allows us to identify how soil particles interact with the textile to cause failure, which would not be possible through experiments alone

Relevance of Work to DOD

Computational tools help identify features of textiles that can improve performance against soil loading for better uniforms, undergarments, or other equipment worn over the extremities. We will be able to provide better protection to prevent or reduce injuries without interfering with the Soldier's ability to quickly maneuver on the battlefield.

Computational Approach

A yarn level model of the Fire-Resistance Army Combat Uniform (FR-ACU) has been developed that allows for individual yarn motion and failure during impact. A total of 49,629 soil particles (0.22g) modeled as smooth particle hydrodynamics (SPH) elements are randomly distributed within a 1 cm diameter sphere. The textile is backed by a soft material that is intended to represent human soft tissue. The model with a comparison to the real FR-ACU is shown in Figure 1. The Sierra Solid Mechanic FE software from Sandia National Laboratories is used to simulate the soil impacting the textile and backing. A stress based failure criteria enables failure of yarns and tearing the in the fabric.

First, we compare the response of the fabric to normal and oblique impact. Next, we explore design aspects by changing the yarn material and composition. The standard FR-ACU is made of staple yarns that contain short rayon, aramid, and nylon fibers spun together. The first variation has yarns made from longer continuous fibers. The second model replaces ripstop yarns with 100% KM2 Kevlar yarns. The last model has all 100% KM2 Kevlar yarns.
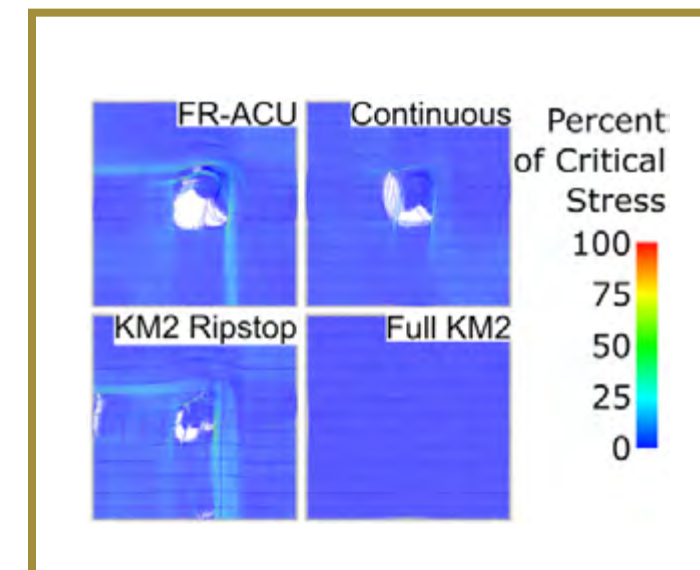
Results

We found that oblique impact allowed the particles to apply a traction to the fabric as a result of particles moving between yarns, folding of the fabric, and the slope of the backing indentation. This traction resulted in yarn failure and tearing compared to the normal impact that produced less stress in the yarn and no failure for this loading scenario. Figure 2 shows a cut plane of the oblique impact where soil-yarn traction is tearing the fabric.

We found that the continuous fiber and KM2 ripstop models reduced tearing after the impact. The full KM2 Kevlar model did not have any yarn failure for this loading. Reduced tearing is important because this will reduce the area of skin directly exposed to the soil spray. Even if some yarns fail, injury can be reduced by maintaining greater uniform coverage.

Future

The current model has helped to illustrate mechanisms of failure and identified several methods to improve the performance of textiles. Future efforts will work to better understand the role of backing material and shape. Additional textile concepts will be evaluated to identify architectures that are ideal for protection against buried blast.

Co-Investigators

Robert Spink and David Fox (CCDC ARL)

Figure 3. A comparison of damage that results from an oblique impact based on yarn construction at 200 μs after impact.

FINITE-ELEMENT MODELS HELP US UNDERSTAND BLAST-INDUCED BRAIN INJURIES

Dr. Jaques Reifman
Telemedicine and Advanced Technology Research Center,
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*Figure 1:
Three-dimensional geometry of rat cerebral vasculature*

Project Description

Exposure to improvised explosive devices (IEDs) can result in various traumatic brain injuries (TBIs), ranging from mild concussions to severe penetrating injuries. Of the more than 350,000 Service members diagnosed with TBI since 2000, 82% are classified as mild TBI, which shows normal structural brain imaging. Although many factors can contribute to mild TBI (e.g., blunt head trauma), what is unclear is whether the mere interaction of blast waves from IEDs with the body can also lead to non-impact, primary blast-induced mild TBI. Animal models can advance our understanding of this injury by clarifying whether blast waves damage brain tissues and, if so, how. To address the latter issue, we also need accurate high-fidelity computational models of animal brains. To inform the development of such models, we performed high-stain-rate testing of rat brain and cerebral vasculature (CV) tissues. Using this new information and an explicit representation of the CV, we recently developed a three-dimensional (3-D) high-fidelity finite-element (FE) rat-head model and validated its predictions for rats exposed to a blast overpressure (BOP).

Relevance of Work to DOD

We cannot extrapolate the results of animal studies to humans without validated scaling laws to translate injuries observed in animals to those in humans. Accurate high-fidelity FE models of animal brains could serve as a means to this end. This capability will help us identify the changes underlying non-contact blast-induced mild TBI and, in turn, specific countermeasures to mitigate the injury.

Computational Approach

We collected micro-computed tomography (μCT) images from rats to obtain the CV geometry (Figure 1), and used the Centennial High Performance Computing (HPC) Machine at the Army Research Laboratory (ARL) to develop a 3-D high-fidelity FE rat-head model that incorporated this geometry, along with the high-strain-rate properties of the face, skull, brain tissues (brainstem, cerebellum, and cerebrum), and CV. We did this by 1) generating a 3-D FE mesh of the CV from the μCT images, 2) integrating this with FE meshes of the face, skull, facial bones, and brain, and 3) coupling the integrated rat-head model with a 3-D FE model of a partial shock tube. We then validated the complete model using data from rats exposed to a BOP in a shock tube.

To test whether the incorporation of CV and high-strain-rate material properties of the rat brain into the model would influence the biomechanical response of the brain to blast waves, we compared how BOPs affected brain pressure, brain strain, and CV strain in three models: one with CV (RHwCV), one without CV (RHw/oCV), and one without CV but using human high-strain-rate material properties (Legacy). As each model had over one million finite elements, we employed ARL HPC Modernization Program resources to perform the simulations.

Results

The CV and material properties of the rat brain did not influence predictions of brain pressure. However, they affected predictions of the magnitude of the maximum principal strain. Strains predicted by the Legacy model, which lacked CV and used the material properties of human brain tissue (stiffer relative to rats), were up to 3 times lower than those predicted by the RHw/oCV model, which used the material properties of rat brain tissue (Figure 2). Incorporation of CV also affected the distribution of the maximum principal strain. Strains at the bottom of the brain did not differ between the RHwCV and RHw/oCV models (Figure 2, left and center), likely because CV is absent in this area. However, strains in other regions were lower for models with CV. For example, the average peak maximum principal strains in the cerebrum, cerebellum, and brainstem in the RHwCV model were 17, 33, and 18% lower, respectively, compared to those in the RHw/oCV model.

Our findings highlight the importance of species-specific material properties and CV in a 3-D high-fidelity FE model of a rat head for assessing the effects of blast exposure.

Future

Together with the Walter Reed Army Institute of Research (WRAIR) and New Jersey Institute of Technology (NJIT), we are examining blast-induced brain injuries and their underlying mechanisms. We will next develop high-fidelity FE brain models of a Göttingen minipig and a human to determine scaling laws.

Co-Investigators

Professor Kenneth Monson (The University of Utah); Dr. Joseph B. Long, Dr. Sujith Sajja, and Mr. Stephen van Albert (WRAIR); Professor Namas Chandra (NJIT)
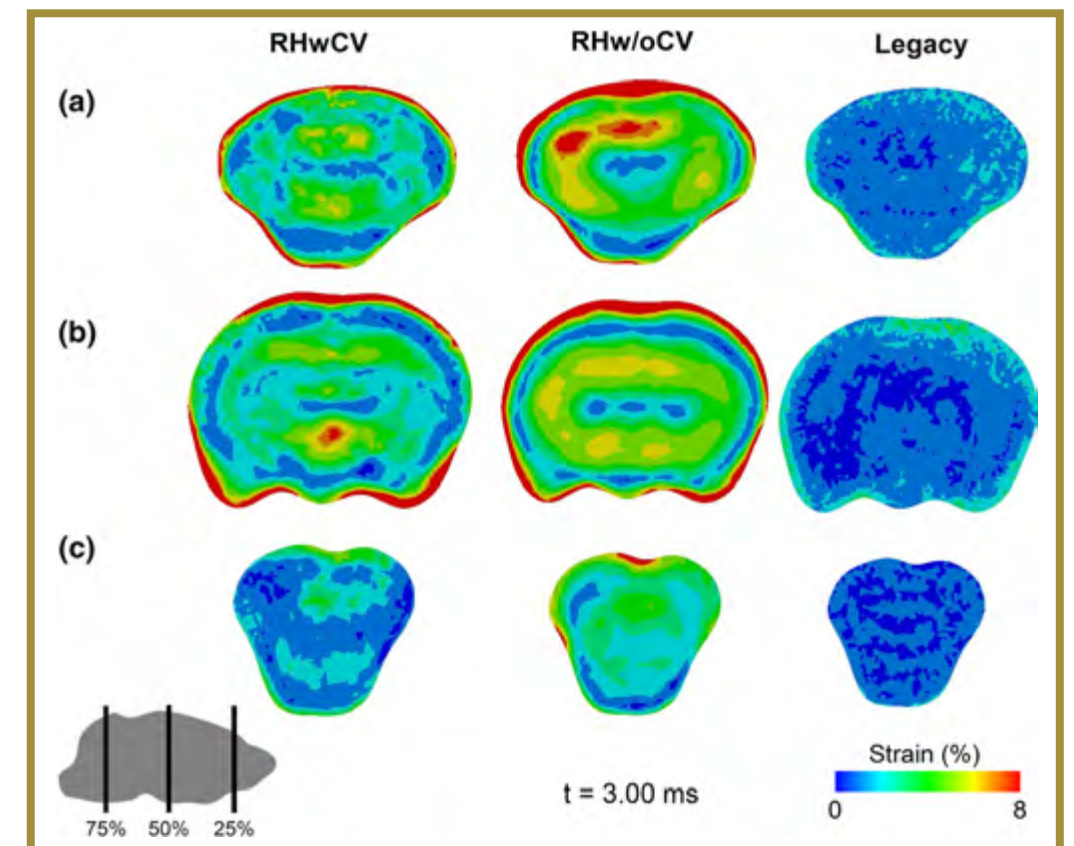

*Figure 2:
Comparison of model-predicted maximum principal strains in coronal plane at the back (75%), center (50%), and front (25%) of the brain*

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