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US Army Artificial Intelligence Innovation Institute (A2I2) Aiding Multi-Domain Operations (MDO)

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14. ABSTRACT

Conflict has been a reoccurring event throughout recorded history. The underlying political goals, the catalysts needed for conflict, typically fall into six broad categories: security, religion, ideological differences, self-determination, strategic objectives, and territory/resources. As technology has evolved, the tactics, techniques, and procedures (TTPs) for conducting conflict have adapted accordingly. Although the TTPs have adapted, the resulting destruction and ruin of infrastructure has remained consistent throughout the ages. US peer and near-peer competitors are fielding multilayered systems to simultaneously fight across multiple domains: space, cyber, air, sea, and land. To maintain friendly operations, the United States faces the challenge of defeating these multilayered systems designed to operate across multiple domains. Emerging technologies like artificial intelligence and machine learning have the potential to defeat these multilayered systems and fundamentally change how conflict is conducted.

15. SUBJECT TERMS

artificial intelligence, AI, machine learning, ML, Army AI Innovation Institute, A2I2, Multi-Domain Operations, MDO, learning, inferencing

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Preface

The first portion of this report explains Multi-Domain Operations (MDO) and movement and maneuver within an MDO environment. Next, examples of the destruction and ruin of infrastructure from urban conflict dating back to World War I and recent natural disasters are provided. The results of conflict and natural disasters, regardless of the time period, are similar. Artificial intelligence/machine learning is discussed throughout. The final portion defines the current US Army Artificial Intelligence Innovation Institute (A2I2) ecosystem.

1. Introduction: The Joint Operational Environment

Joint Operating Environment 2035 predicts that for the foreseeable future US national interests will face challenges from both persistent disorder and states contesting international norms.[1] It defines persistent disorder as an array of weak states that become increasingly incapable of maintaining domestic order or good governance. Contesting international norms involves increasingly powerful revisionist states and select nonstate actors using all elements of power to establish their own set of rules unfavorable to the United States and its interests. Adversaries seek to fracture US alliances and partnerships through a combination of diplomatic and economic actions, unconventional warfare, information warfare, exploitation of social, ethnic, or nationalistic tensions in a region, and the actual or threatened employment of conventional forces.[2] Our adversaries will rely on ambiguity and uncertainty to create strife between groups and to counter US standoff intelligence, surveillance, and reconnaissance (ISR) capabilities and strike power projection. An increasingly prevalent form of information warfare is the "firehose of falsehood": fabricated stories distributed by paid "trolls" or automated "bots", which unsuspecting citizens amplify through social media or other means, to confuse audiences or divert attention from adversaries' intentions.[3]

The US Army Training and Doctrine Command (TRADOC) has developed a Multi-Domain Operations (MDO) framework for countering adversaries contesting international norms by fracturing US alliances and partnerships. TRADOC Pamphlet 525-3-1[2] describes the MDO framework to counter how our adversaries have expanded the battlefield in 1) time (phases), 2) domain, 3) geography (space and depth), and 4) actors. Domain includes land, air, maritime, space, and cyberspace. The expansion of the battlefield blurs the distinction between actions "below armed conflict" and "conflict", enabling the achievement of strategic objectives short of what the United States traditionally considers "war". The MDO framework defines how the US Army will compete, penetrate, "dis-integrate", and exploit adversaries that challenge international norms.

The MDO framework objectives are to 1) defeat an adversary's destabilization efforts, 2) compete in the envelope below armed conflict, 3) deter armed conflict, 4) if conflict breaks out, penetrate anti-access and area-denial systems, 5) dis-integrate an adversary's destabilization efforts and anti-access and area-denial systems, and 6) exploit gains by returning to international norms.

MDO is conducted across multiple domains and contested spaces to overcome an adversary's effort to challenge international norms by presenting them with several operational and/or tactical dilemmas through the combined application of calibrated force posture, employment of multi-domain formations, and convergence of capabilities across domains, environments, and functions in time and space to achieve operational and tactical objectives.[2] TRADOC Pamphlet 525-3-1 defines calibrated force posture as the combination of position and the ability to maneuver across strategic distances. It includes but is not limited to basing and facilities, formations and equipment readiness, distribution of capabilities across components, strategic transport availability, interoperability, access, and authorities. Calibrated force posture allows Army forces to support joint-force objectives in competition, deter armed conflict by preventing adversaries from attempting a fait accompli attack on favorable terms, and enable friendly forces to quickly seize the initiative in large-scale combat operations by setting the theater for expeditionary forces. In short, commanders seek to create multiple dilemmas to prevent an enemy force from reacting in an organized fashion. They achieve this by moving forces to positions that compel enemy decisions that favor the friendly commander.[4]

MDO seeks to maintain international norms with the least amount of armed conflict possible. When conflict does break out, commanders conduct operations by leveraging warfighting functions, which include mission command, movement and maneuver, intelligence, firing, sustainment, and protection. Warfighting functions are the physical means that tactical commanders use to execute operations and accomplish missions by superior tactical and operational-level commanders. The purpose of the warfighting functions are to provide an intellectual organization for common critical capabilities with other warfighting functions to achieve objectives and accomplish missions.[5]

2. Foundation for the US Army Artificial Intelligence (AI) Innovation Institute

Emerging autonomous robotic systems are increasingly used to augment, rather than simply replace, individuals and platforms. The augmentation of human systems with robotics, particularly swarming, will permit longer-duration missions, improve the ability to protect capital platforms from attack, and increase individual human and unit performance.[6] Capital platforms consist of technologies that require specialized infrastructure, highly trained science, technology, engineering, and mathematics (STEM) personnel, and large funding investments across multiple organizations. Capital platforms provide overmatch capability against peers and near-peers for those nations that have the STEM resources, infrastructure, and finances.

A key goal of AI/machine learning (ML) is to provide augmented intelligence for the warfighter during MDO. AI/ML can effectively deal with the large amounts of data, increasing the speed of action. The improved data analytics enables enhanced decision making and reduces manpower requirements. The AI model must be employed with resilience (when physically and virtually isolated) and must operate in complex (often urban) environments that are very dynamic, distributed, resource-constrained, fast-paced, and contested. Our adversaries will use urban areas to negate US standoff reconnaissance and strike advantages by creating sheltered locations hidden within urban clutter. The joint force will either fight or attempt to contain adversaries within and across urban agglomerations that sprawl over hundreds of square miles, are located in littorals, and contain tens of millions of people. They will typically feature subterranean infrastructure, shantytowns, and skyscraper canyons in varying states of functionality and disrepair. This built-up environment can degrade or reduce mobility as well as the effectiveness of advanced weapons, communication systems, and ISR capabilities.[6]

The challenges associated with MDO missions in these degraded and reduced-mobility urban environments will be mitigated by teaming warfighters with intelligent agents. To offset demand on maneuver support forces, units integrate emerging technology such as unmanned aircraft systems, AI, robotics, and autonomous systems. Advanced sensors and autonomous robotic systems teamed with Soldiers enable integrated security operations, allowing formations to conduct continuous reconnaissance, early warning, and to maintain enemy contact, including in the cyber domain. These capabilities enable maneuver formations at all levels to move to positions of advantage rapidly and enter fights at unexpected locations.[6]

These intelligent agents will consist of highly distributed and integrated autonomous ground and airborne systems that provide ISR at the point of need. The Army has unique technical challenges associated with MDO in urban environments that other military services and the commercial sector do not address, especially for the Next Generation Combat Vehicle and command, control, communications, computers, and intelligence (C4I). All units performing offensive tasks should expect to operate in a contested and degraded communications environment. Degradation may arise from environmental circumstances, enemy action directed against friendly communications and information systems, or malfunctions. A degraded communications environment may be permanent or temporary. Enemies use several methods to deny friendly use of the cyberspace domain and the electromagnetic spectrum. These methods include cyberspace attack (digital attack against Army, joint, and other networks), electronic attack (jamming of portions of the electromagnetic spectrum), and physical attack against infrastructure and electronics.[5] Army MDO will increasingly 1) operate with extreme C4I resource and size, weight, and power, time (SWaPT) constraints, 2) learn in complex data environments with small, highly cluttered data samples, and 3) rely on rapidly adaptable human–AI teams that learn from human understanding of high-level goals. Most importantly, reliance by the warfighter on AI at the point of need for improved human decision making in both speed and accuracy will require AI/ML that is reliable, adaptable, and robust. To protect the safety of the warfighters and success of missions, a fundamental understanding of deployed AI/ML is required that can predict intelligent system behavior, performance, and limitations across a variety of situations.

3. Differences between Commercial and MDO Datasets

Most current research in AI/ML is accomplished with extremely large collections of relatively clean and well-curated training and testing datasets, with little background noise and no deception. Military domains are very distinct from commercial applications because of 1) rapidly changing situations, 2) limited access to real data to train and test AI, 3) noisy, incomplete, uncertain, and erroneous data inputs during MDO in military environments, and 4) peer adversaries that employ deceptive techniques to defeat algorithms.

4. Commercial Self-Driving Car Datasets

Waymo, formally known as the Google Self-Driving Car Project, has collected data by driving millions of miles on paved roads and billions of miles in simulated driving. Prior to driving on a new road, Waymo builds detailed 3-D maps that provide information on the road profile, curbs, sidewalks, lane markers, crosswalks, traffic lights, and stop signs. Waymo sensors and software scan constantly for objects around the vehicle—pedestrians, cyclists, vehicles, road work, obstructions, and so on—and continuously read traffic controls, from traffic light color and railroad crossing gates to temporary stop signs.[7]

5. Movement and Maneuver

Movement generally occurs outside of enemy direct-fire contact. The three movement techniques used to describe movement are traveling (contact not likely), traveling overwatch (contact possible), and bounding overwatch (contact expected). Maneuver is what commanders execute when in contact with the enemy. Direct fire and close combat are conditions inherent to maneuver. Leaders use forms of maneuver to describe their actions. Commanders use combinations of movement and maneuver to avoid enemy strengths and to create opportunities to increase the effects of friendly fires.[4]

6. Decision-Support Tool Datasets for Movement and Maneuver

Decision-support tools, such as aided target recognition and automatic target recognition, rely on a wide variety of data types and information sources to aid in observing the environment, establishing situational awareness, and selecting the best available assets for performing appropriate actions. Various airborne and ground-based sensor modalities (e.g., acoustic, radar, electro-optical, and IR) are leveraged to determine the best available solutions for performing the actions.

The quantity, quality, and variety of the data are important for both training AI models and testing the performance of the AI models. Sensor data must cover a wide range of mission-representative environmental conditions such as variations in lighting and weather. Additionally, the data must address target/sensor parameters, providing a variety of perspectives, sensor–target ranges, and fields of view (FOVs).

The Army has a great deal of data at development, training, testing, and operational centers. However, before the data can be provided to AI developers, the data must be assessed to determine if they are suitable for AI model training and testing. The associated metadata, in addition to the acoustic, radar, electro-optical, and/or IR data, must also be included for the data to be useful for AI developers. Examples of metadata include 1) date, time, and location of collection, 2) high-level sensor and platform description, 3) sensor specifications, to include but are not limited to sensor manufacture/model, resolution (e.g., 640 × 480 pixels), wavelength, aperture, FOV, and the like, 4) sensor data type (e.g., full motion video, wide-area motion imagery, among others), 5) data standard used, such as the Motion Imagery Standards Board and Standardization Agreement, 6) data format used, such as Key Length Value and Augmented Reality System, among others, 7) compression methods and levels used, 8) independent frames or video (e.g., number of frames per second, 9) target set or type of target to include GPS logs, 10) information on labeling/annotation formats (e.g., Microsoft Common Objects in Context or specific key/value pair descriptions), 11) environmental conditions such as terrain and weather, 12) custom file readers or schemas for nonstandard file formats, 13) points of contact familiar with the data and data collection event, 14) security classification guidance and distribution statements, and 15) data previously provided (e.g., by academic or commercial partners to performers, which determines if the data can be used for independent testing purposes).

The Department of Defense (DOD) motto "Train Like You Fight" best captures the relationship between AI model training data (train) and AI model testing (fight) data. The collection of quality data for AI-based decision-support tools is not a trivial task; it is not as simple as taking pictures of military vehicles. As stated previously when discussing the mining of legacy Army data, the metadata are just as important as the acoustic, radar, electro-optical, and/or IR data.

7. Movement and Maneuver Environments

Combat vehicles will incorporate autonomous systems both on and off the vehicle. Autonomous systems assist in operating, targeting, protecting, and maintaining onboard systems. Off-board systems will provide intelligence, surveillance, reconnaissance, protection, and additional lethality options to the manned combat vehicle.[6] The MDO movement and maneuver environments are dynamic, uncertain, complex, contested, sometimes austere, and sometimes built-up. The environments that AI is to operate in provide many unique technical challenges.

Figure 1 provides an example of an off-road environment. US Soldiers with Delta Troop, 1-150th Cavalry Regiment, 30th Armored Brigade Combat Team operated an M1A1 Abrams main battle tank (MBT) as part of armament accuracy checks and boresight procedures leading up to the live-fire accuracy screening test in the vicinity of Fort Bliss, Texas, on 16 September 2019.[8] The terrain is relatively benign, with little to no natural or man-made obstacles. Vegetation is limited and easy to maneuver around.

Fig. 1 Example of M1A1 Abrams MBT off-road environment

Figure 2 provides an example of an M1A1 Abrams MBT assigned to 6th Squadron, 8th Cavalry Regiment, 2nd Armored Brigade Combat Team, 3rd Infantry Division guarding a fighting position during Spartan Focus at Fort Stewart, Georgia, on 6 March 2019.[9] The terrain's dense vegetation inhibits maneuver.

Fig. 2 M1A1 Abrams MBT guarding a fighting position

8. The Nature of Urban Areas

Although urban areas have similar characteristics, no two are identical. Urban areas vary in terms of population density, construction, culture, and many other factors. The dynamic variety of natural and manmade features in urban areas presents commanders with a multitude of challenges. This physical terrain consists of man-made structures of varying types, sizes, materials, and construction, sometimes arranged in an orderly manner and sometimes randomly. It may be modern or built around an ancient core, and it may contain towering buildings or none over three stories. The nature of the conflict, the attitude of the population, and the purpose of friendly operations during urban operations interact in ways that vary case by case, potentially even in different cities in the same country. While urban terrain describes the physical nature of the environment, perhaps the most-important mission variable to consider is the people within cities and their surroundings.[10]

Urban areas confine movement and maneuver, reduce technological overmatch, strain ISR capabilities, make target acquisition and tracking difficult, and impact tactics, techniques, and procedures (TTPs). Urban conflict is very labor- and time-intensive compared with conflict in other environments because the battlefields in urban areas are stacked vertically. Additionally, the infrastructure provides cover and concealment from sensors and reconnaissance, resulting in short exposure times. This reduces the overall timeline for sensing, acquiring, tracking, and identifying threats.

9. Urban Conflict Environments and Humanitarian Aid and Disaster Relief (HADR) Missions

As stated previously, the collection of quality data is important for both training AI models and testing the performance of the AI models. The most difficult environment from both a data collection standpoint and mission operational standpoint is the urban environment. The datasets collected to train and test the intelligent agents for conflict or HADR in an urban environment will be very difficult to collect because of the nature of the damage. The following figures provide examples of the operational environment during urban conflict and HADR missions. Figure 3 shows Villers Carbonnel, France, after an artillery bombardment during World War I.[11] Buildings were reduced to rubble and streets were impassible. Figure 4 shows the battle damage at the Village of Vaudettoie, France, during World War I.[12] Once again, buildings were reduced to rubble and streets were impassible. Figure 5 shows a battle-damaged, debris-filled street in Fallujah, Iraq, on 27 November 2004.[13] Figure 6 shows the damage in Aguadilla, Puerto Rico, after Hurricane Maria on 23 September 2017.[14] Figure 7 shows Oklahoma Army National Guard personnel conducting HADR operations in El Reno, Oklahoma, after a tornado cased damage on 26 May 2019.[15] Current AI model techniques require labeled datasets to train and test AI models for use in urban conflict or for HADR missions. These datasets will need to characterize the rubble and randomness associated with urban damage—a seemingly endless number of combinations.

Fig. 3 Villers Carbonnel, France, after an artillery bombardment during World War I[11]

Fig. 4 Village of Vaudettoie, France, battle damage during World War I[12]

Fig. 5 Debris-filled street In Fallujah, Iraq, 27 November 2004[13]

Fig. 6 Aguadilla, Puerto Rico after Hurricane Maria, 23 September 2017[14]

Fig. 7 Oklahoma Army National Guard personnel conducting HADR mission[15]

10. AI Capabilities Overview for MDO

AI capabilities are related to the way the model trains. Model training can be categorized as 1) supervised learning, 2) unsupervised learning, 3) semi-supervised learning, 4) transfer learning, and 5) reinforcement learning. The style of learning is characterized by its training data and the attributes of the available training data.

Supervised learning consists of training the model with labeled datasets. A label may identify a discrete class, a continuous computed value, a state, and so on. Supervised learning is considered task-driven since it is dependent on the type of task being conducted. Target classification (e.g., classifying objects in imagery) is one type of task that can successfully use this style.

Unsupervised learning consists of training the model without labeled datasets. Current use examples of this data-driven learning include clustering, anomaly detection, association rule learning, and dimensionality reduction (i.e., identifying the most-significant features of the data).

Semi-supervised learning consists of training the model with both labeled and unlabeled datasets. This type of learning method is used when the task is the same but the operational environment is different from the trained environment. Current use examples include speech analysis, knowledge organization, classification, and regression. Semi-supervised learning is hybrid task data-driven.

Transfer learning consists of training the model with data available in one domain but with only limited training data available in a related domain. This involves adapting a previously trained model to a new, related target problem. This extends the semi-supervised learning to the cases where the trained and operational tasks are different, or when the tasks are the same but the operational environment is different from the trained environment. Current use examples include document classification and learning from simulations. Transfer learning is for new domains.

Reinforcement learning consists of training the model to be goal-driven. This focuses on learning from experience, usually by giving the model a “reward”. Reinforcement learning can be considered a way to react to the environment to achieve a goal. Current use examples include robotic mobility, games, and predictive maintenance.

11. Army AI R&D Infrastructure

The next two decades will see significant advances in autonomy and AI, to include the emergence of robots working together in groups and as swarms. New and powerful robotic systems will be used to perform complex actions, make autonomous decisions, deliver lethal force, provide ISR coverage, and speed response times over wider areas of the globe.[1] The Army will try to extend advances achieved by the AI commercial sector—the leaders in this technology space—through partnerships and collaborative efforts. Commercial capabilities could be leveraged as the building blocks for MDO with teams of highly dispersed warfighters and agents (robotic and software) operating in harsh conditions and dynamic environments. Autonomous unmanned systems will be capable of movement in complex terrain and environments equal to or greater than their human counterparts.[6]

The Army faces rapidly changing, complex, never-before-seen situations where 1) existing AI training and testing datasets will not be representative of the ever-changing operational environment (e.g., movement and maneuver, and urban conflict), 2) tactical training data will be noisy, incomplete, erroneous, and not well curated, and 3) adversaries will employ deceptive techniques to defeat AI algorithms. The Army requires AI that will learn using small, unlabeled datasets, collected organically and in real time, that will 1) quickly and easily adapt to new tasks, 2) provide context and understanding in unstructured environments, and 3) defeat attacks from adversarial machines.

12. US Army AI Innovation Institute (A2I2) Concept

The US Army Combat Capabilities Development Command (CCDC) Army Research Laboratory (ARL) will foster AI/ML technologies by focusing A2I2 on rapidly advancing AI capabilities for movement and maneuver during MDO. A2I2 is an AI ecosystem (Fig. 8) consisting of the 1) CCDC Army Research Laboratory

Open and Extended Campuses, 2) Network Science Research Laboratory (NSRL), 3) Secure Unclassified Network (SUNet), 4) Defense Research and Engineering Network (DREN), 5) ARL High-Performance Computing (HPC), 6) Automated Online Data Repository (AODR), 7) an assortment of AI software tools, and 8) interdisciplinary subject-matter experts (SMEs).

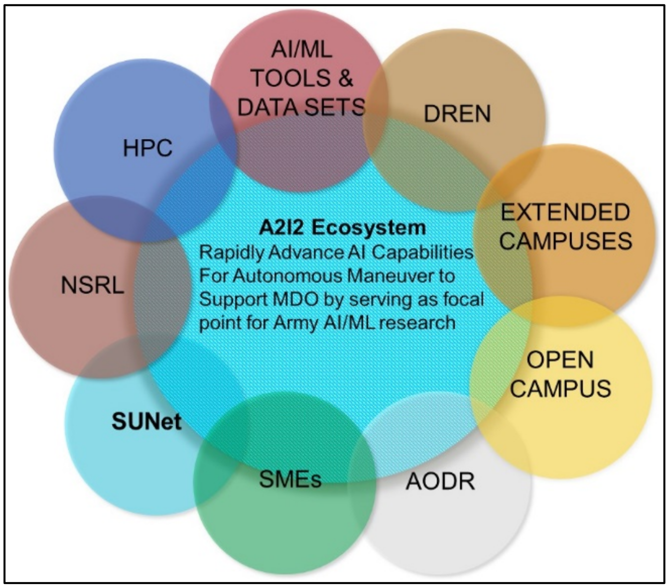

Fig. 8 A2I2 ecosystem

AI will provide our warfighters with the ability to recognize, with one glance, the tactical advantages and disadvantages on the battlefield using a heterogeneous mix of unmanned ground and aerial platforms that rapidly learn, adapt, and reason in complex and dynamic environments. These physical agents will interact with Soldiers as teammates with a shared understanding to jointly respond to dynamic events while encountering adversarial deception at the speed of the fight. Autonomous unmanned systems will respond to digital and verbal commands and act as members of the squad or crew. They will provide accurate verbal and written language translation unobtrusively. Autonomous unmanned systems will function as members of the formation, executing tasks as well as providing oversight for subordinate systems. This capability will allow leaders to employ unmanned systems for critical and complex tasks such as establishing a mesh communication network or reconnoitering and mapping subterranean infrastructures.[8]

13. A2I2 Vision

The A2I2 vision is to develop and employ a suite of AI to provide intelligent systems that assist Soldiers in dynamic, uncertain, complex, contested, austere, and congested operational environments. The intelligent systems will reduce the dangerous, physically demanding, and routine tasks required of Soldiers and crew members.[6] A2I2 will develop intelligent agents for the battlefield—heterogeneous and distributed—that rapidly learn, adapt, reason, and act in these environments; specifically, AI agents that 1) learn, adapt, reason, and act using small datasets of noisy, dynamic, deceptive data, 2) learn, adapt, and reason in a dynamic, distributed manner over highly heterogeneous data with impaired C4I, 3) perform computations under extreme SWaPT constraints, and 4) process at the point of need. Commanders, when supported by mission-command systems that can access current and accurate information, exploit their understanding of the enemy and friendly situations. This understanding allows maneuver at favorable ranges and ensures responsive and flexible support of forces. The integration of information technologies, capable leaders, and agile formations reduces risk and facilitates decisive action.[4]

14. A2I2 Goals

A2I2 will focus on addressing unique Army AI technical challenges. The overarching A2I2 goals are to 1) focus AI researchers on technical challenges faced by future Army MDO, 2) serve as a focal point and catalyst for Army AI innovation, 3) develop a fundamental understanding of AI in order to predict model performance in various MDO phases, domains, geographies, and environments, 4) create a robust training, testing, and experimentation process for rapid assessment in Army-relevant MDO conditions, and 5) rapidly mature promising research algorithms and models for transition to the warfighter.

15. A2I2 Integrated Strategy

A2I2 will pursue an integrated strategy for accelerating the fundamental understanding, development, training, testing, experimentation, and transition of AI for Army MDO. The strategy is to develop teams that consist of 1) Army AI/ML researchers from ARL, to include Open and Extended Campuses, 2) researchers from academia and industry, 3) interdisciplinary technical teams for collecting unique datasets for training and testing, 4) interdisciplinary teams, to include the user community, for planning and executing MDO-representative experiments in realistic environments, and 5) transition partners to field AI models to appropriate platforms.

15.1 Collaborative Alliances and Partnerships for Government–Private-Sector Collaboration

ARL uses collaborative alliances to address research problems that require a multidisciplinary research approach to make significant progress. These alliances are uniquely designed to 1) accelerate the development of AI/ML for the Army with a model that enables government–private-sector collaboration and exchange, 2) create an open research environment where ideas are shared freely, and 3) flexibly adjust research efforts on the fly to adapt to emerging trends. Alliances consist of a competitively selected consortium of academia and industry that, when combined with ARL, forms an alliance. The alliance is structured and managed to foster an open collaborative research environment to allow deep collaboration among government and private-sector researchers to conduct multidisciplinary research. This is enabled by an innovative acquisition model that allows and encourages government scientists to collaborate, co-invent, and co-publish with private-sector researchers. To develop a shared understanding and to cultivate these collaborations, the alliance encourages frequent technical interchanges and long- and short-term staff rotations. A series of competitively selected basic and applied research tasks jointly developed by the alliance encourages new ideas, allows new researchers to join the alliance, and adapts to emerging technical gaps and scientific breakthroughs. The innovative use of agreements affords ARL significant flexibilities to 1) adjust alliance research on the fly without contractual negotiations, 2) add and remove research organizations and researchers to accommodate new, innovative ideas or emerging research trends, 3) augment research with government staff as they become available, and 4) fully embed alliance research in the ARL enterprise. This acquisition agility is critically important for impacting the rapidly expanding field of AL/ML.

15.2 Open and Extended Campuses

Critical to developing AI/ML capabilities for the Army is the ability of A2I2 to attract, house, and support AI researchers. Key enablers are ARL's Open and Extended Campus initiatives, which provide an incubator for collaboration with Army and other private-sector researchers in a variety of locations.

15.2.1 Open Campus

ARL's Open Campus[16] is a collaborative endeavor with the goal of building a science and technology (S&T) ecosystem that will encourage groundbreaking advances in basic and applied research areas of relevance to the Army. Through the Open Campus framework, ARL scientists and engineers work collaboratively and side by side with visiting scientists in ARL's facilities and as visiting researchers at collaborators' institutions. Central to the research collaborations is mutual scientific interest and investment by all partners—ARL's Open Campus is not a funding opportunity. The global academic community, industry, small businesses, and other government laboratories benefit from this engagement through collaboration with ARL's specialized research staff and unique technical facilities. These collaborations will build research networks, explore complex and singular problems, enable self-forming expertise-driven team building that will be well-positioned for competitive research opportunities, and expose scientists and engineers, including professors and students, to realistic research applications and perspectives, helping ensure our nation's future strength and competitiveness in these critical fields.

Key characteristics of the Open Campus initiative are include the following:

- Open sharing of ARL facilities and research opportunities for all partners, including foreign nationals
- Synergistic relationships with the international, academic, and entrepreneur communities
- Creation of flexible career paths in defense research that allow easy transition between government, academia, and industry
- Investment in and strategic sharing of human capital and state-of-the-art facilities and technical infrastructure across government, industry, and academia
- Enhanced defense research environment that fosters innovation, collaboration, and scientific/engineering growth and provides an incubator for rapid transition of technologies into products by entrepreneurs
- Increased opportunities for technology advancement and transfer of research knowledge
- Increased public involvement in defense research to create enhanced understanding of the value and importance of defense science, technology, and exploration

ARL's Open Campus initiative creates an agile, efficient, and effective laboratory system that supports the continuous flow of people and ideas to ensure the successful execution of the technical strategy.

This has been accomplished at ARL locations with 1) layered security mechanisms, 2) commercial network access so that US and international researchers can collaborate while sensitive programs are shielded, and 3) robust processes to reduce bureaucracy and enhance the collaboration experience. Visiting researchers have access to open areas and laboratories and can engage in continuous, co-located collaboration with Army researchers.

15.2.2 Extended Campuses

ARL Extended,[17] through co-location of Army R&D personnel and close collaboration on research and innovation activities, is an effort to create strong, enduring S&T partnerships working together to solve the Army's current and future challenges. Through the Open Campus initiative, ARL Extended leverages regional expertise and facilities to accelerate the discovery, innovation, and transition of S&T.

ARL is significantly expanding the Extended Campus ecosystem to campuses throughout the United States to 1) create synergistic relationships with academic and entrepreneurial communities, 2) foster open sharing of ARL facilities and research opportunities for all partners to solve Army technology needs, 3) enable flexible career paths to allow transition between government, academia, and industry, 4) create an incubator for rapid transition of technologies into products, 5) increase public involvement in defense research, 6) provide access to a large pool of SMEs from academia and industry, and 7) capitalize on strong academic institutions and graduates with regional preference.

Several areas of the country have been identified as tech centers where ARL would like to have an increased presence to work with regional expertise, identified as ARL West, Central, South, and Northeast. The human talent in these regions is not necessarily concentrated at a single university, which necessitates a "hub and spoke" model. The ARL regional leader resides at the hub to coordinate and manage activities for a given territory. Additional staff may be located in outstations or spokes with university partners not in the immediate vicinity of the regional lead. Continuing partnerships at each of the sites are re-evaluated regularly as ARL priorities and partner interests evolve. It is projected that, over time, approximately 15% of the ARL workforce will reside at these new campuses. ARL is also engaging other Army, DOD, and non-DOD organizations to enable their participation as well.

15.2.2.1 ARL West Focus Areas

ARL West[18] focus areas include the following:

- Human information interaction
  - Contextual analytics

    - Hybrid human interfaces
    - Integrated analysis and assessment
    - Joint human–agent decision making
- Cybersecurity
- Embedded processing
- Intelligent systems

15.3.2.2 ARL Central Focus Areas

ARL Central[19] focus areas include the following:

- HPC
- Impact physics
- ML/data analytics
- Materials and manufacturing
- Power and energy
- Propulsion science
- Quantum science

15.3.2.3 ARL South Focus Areas

ARL South[20] focus areas include

- AI/ML
- Energy/power
- Cybersecurity
- Bio/directed energy
- Materials and manufacturing
- Networks

15.3.2.3 ARL Northeast Focus Areas

ARL Northeast[21] focus areas include the following:

- Materials and manufacturing sciences

- AI and intelligent systems
- Cyber and secured communications at the tactical edge

16. Network Science Research Center (NSRC)

The Army battlefield of the future will be a complex, dynamic, heterogeneous network involving multiple interacting actors and agents, generating a massive volume of data. The Army will require a means of controlling, channeling, directing and reshaping this dynamic and cluttered information field. ARL formed the NSRC[22] to foster collaborative research needed to assess, model, predict, and influence the complex behaviors and interactions between large- and small-scale communication, information, and social-cognitive networks.

The NSRC brings together a multidisciplinary team of researchers from across ARL to advance network science across several fronts including the following:

- Design and control of complex multi-genre networks
- Semantically and quality-aware networking
- Heterogeneous information fusion
- Trust management theory
- ARL Experimentation Framework: provides an integrated environment capable of modeling and visualizing complex network science experiments
- ARL Dynamically Allocated Virtual Clustering Management System (DAVC): a cloud environment for experimentation
- ARL Visualization Framework: a suite of visualization tools

The NSRL[22] is one of the unique facilities within NSRC.

17. Network Science Research Laboratory

The NSRL is built for real-time modeling of mobile network systems, providing a controlled, repeatable emulation and simulation environment. NSRL provides a collaborative experimentation workspace for multidisciplinary research teams to experiment, prototype, and demonstrate AI/ML. It is composed of a suite of hardware and software that models the operation of mobile networked device RF links through simulation, enabling experimental validation or falsification of theoretical models, and characterization of protocols and algorithms for mobile wireless networks. The laboratory is set for a range of experiments, from assessing in-network aggregation of network information for detecting cyber threats to characterizing the impact of communications disruption on analytics delivered to Soldiers at the point of need. The NSRL environment is the result of collaborative efforts between ARL and the US Naval Research Laboratory. Using NSRL capabilities, researchers can 1) model link and physical layer connectivity in real time, 2) implement actual network protocols and application software (mimics real-world mobile, wireless network systems), 3) provide event-driven control and logging facilities, and 4) use a distributed architecture.

DAVC is one of the primary experimentation infrastructure components within NSRL that enables researchers to dynamically create, deploy, and manage virtual clusters of heterogeneous nodes within a cloud-computing environment. The system extracts test-bed configuration complexities by automatically assigning and configuring virtual cluster networks and network services. The virtual clusters deployed within DAVC can be used for a wide variety of tasks, such as software development, experimentation, and existing hardware/software integration. DAVC enables researchers to configure robust networking scenarios and complex subnet hierarchies within each cluster. Each cluster is assigned private virtual local area networks, which restrict network traffic within the boundaries of a specific cluster. This also eliminates undesirable crosstalk between clusters and researcher's experiments, allowing for multiple experiments to be conducted simultaneously.

18. Experimentation and Assessment

The ability to design and conduct MDO-based experiments, and to learn from the resulting insights, is a key enabler for the Army to field AI/ML capabilities. A2I2 will conduct a full range of MDO-based experimentation to include 1) data science experiments with unlabeled and labeled data, 2) repeatable emulations in MDO-representative environments using existing TTPs, 3) controlled experiments with autonomous platforms, 4) cognitive performance simulations to assess human–agent performance under controlled and repeatable conditions, and 5) full-scale field experiments. The experimentation overarching objectives are to 1) rapidly design and conduct experiments in MDO-representative environments to engage researchers and to keep pace with technology advances, 2) progress through a full spectrum of experiments ranging from relevant (open) to realistic (sensitive) to real (classified) environments to ultimately providing capabilities for warfighters, and 3) adopt experimentation approaches for AI/ML involving networks, sensor networks, autonomous platforms, and joint human–AI learning.

19. Networks

A2I2 will leverage a variety of ARL networks available to both the Open and Extended Campuses as well as the extended research community to support data exchange and experimentation.

19.1 SUNet

SUNet is a US-government-established, non-DOD information-network, For Official Use Only–accredited unclassified platform. SUNet provides an operational infrastructure that is secure, accredited, Internet-accessible, unclassified, scalable, and with user/data segmentation and strict access controls. SUNet enables mission partners to establish virtual enclaves, controlled access to those enclaves, and to acquire, develop, and deploy mission-specific datasets and analytics that can be shared across multiple enclaves or restricted based on mission requirements. SUNet serves US federal government agencies as well as law-enforcement agencies from around the world to support collaborative efforts.

19.2 DREN

DREN is a high-speed, high-capacity, low-latency nationwide computer network for computational scientific research, engineering, and testing in support of the DOD S&T and test and evaluation communities. DREN connects scientists and engineers throughout DOD's geographically dispersed HPC user sites, including the five DOD Supercomputing Resource Centers (DSRCs) and more than 150 user sites at other government laboratories; research, development, and engineering centers; university affiliated research centers; test centers; universities; and industrial-partner locations throughout the United States. A2I2 can capitalize on the already established DREN infrastructure for generalized HPC and add processor bays tailored to performing AI/ML while employing existing staff to maintain the new systems. Use of DREN allows experimentation with new computing systems and algorithms without endangering or overburdening the DOD enterprise network. For classified or sensitive research, the Secret DREN is used to connect with dedicated HPC assets.

19.3 HPC

ARL hosts one of five DSRCs for HPC. It is located within the ARL Supercomputing Research Center and features state-of-the-art, scalable, parallel architectures and large vector-parallel systems supporting both classified and unclassified missions throughout DOD's research, development, test, and evaluation community. Figure 9 depicts the range of existing HPC research partners. DSRC has over 50 SME programmers and hardware maintenance personnel. These experts are available to teach users how to use the HPC and to help them develop tailored tools and algorithms unique to their research or data analysis needs. The DSRC is critical for technology-based research; it enables optimized design, development, and testing and minimizes lifecycle acquisition costs. Current ARL HPC systems have a cumulative capability of 1.1 petaflops and are ranked in the top 15% of the world's most-powerful computing sites.

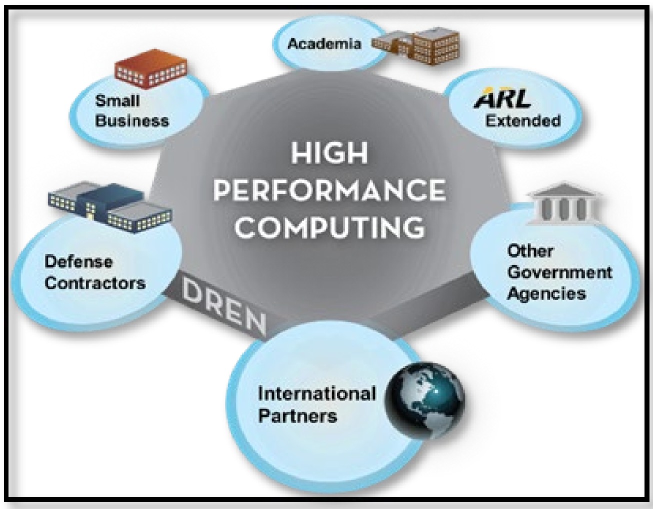

Fig. 9 HPC research partners

20. AODR

AODR stores structured and unstructured data from disparate sources with security and access control for open and sequestered data. Key attributes include 1) a central repository for data produced in ISR exercises/demonstrations and experimental research data, 2) accessible data available to the research community (government, industry, and academia), 3) "gold" repository for reference and sequestered data for development and evaluation of tools and algorithms, 4) developers have common access to latest and most-relevant data, 5) data owner retains ownership and decision authority and is in the approval chain regarding distribution of their data, and 6) each dataset has its own data request form/data use agreement/nondisclosure agreement. Open-source technologies, including free and open-source file formats for video and imagery, are used. AODR contains multimodal signature data collected during field exercises and demonstrations to facilitate R&D of analytical tools and algorithm development supporting the ISR community. AODR is a central repository for standards-compliant datasets and serves as a go-to location for lessons learned and reference products. It allows researchers to request copies of stored data and for the government to process the request through an automated approval system. Sensor modalities currently offered include 1) acoustic, 2) magnetic, 3) seismic, 4) passive IR, 5) E-field, 6) visible broadband imaging, 7) visible to near-IR, 8) shortwave IR, 9) longwave IR hyperspectral imaging, 10) synthetic aperture radar, 11) ultra-wideband ground-penetrating radar, 12) laser-induced breakdown spectroscopy, and 13) Raman spectroscopy.

21. Conclusion

Joint Operating Environment 2035[1] predicts that for the foreseeable future US national interests will face challenges from both persistent disorder and states contesting international norms. Adversaries seek to fracture US alliances and partnerships through a combination of diplomatic and economic actions, unconventional warfare, information warfare, exploitation of social, ethnic, or nationalistic tensions in a region, and the actual or threatened employment of conventional forces. TRADOC has developed an MDO framework for countering adversaries contesting international norms by fracturing US alliances and partnerships. The MDO framework objectives are to 1) defeat an adversary's destabilization efforts, 2) compete in the envelope below armed conflict, 3) deter armed conflict, 4) if conflict breaks out, penetrate anti-access and area-denial systems, 4) dis-integrate adversary's destabilization efforts, anti-access, and area-denial systems, and 5) exploit gains by returning to international norms. A key goal of AI/ML is to provide augmented intelligence for the warfighter during MDO. AI/ML can effectively deal with the large amounts of data, increasing the speed of action. The improved data analytics enables enhanced decision making and reduces manpower requirements. Decision-support tools, such as aided target recognition and automatic target recognition, rely on a wide variety of data types and information sources to aid in observing the environment, establishing situational awareness, and selecting the best available assets for performing appropriate actions. The quantity, quality, and variety of the data are important for both training AI models and testing the performance of the AI models. The DOD motto "Train Like You Fight" best captures the relationship between AI model-training data (train) and AI model-testing (fight) data. ARL will foster AI/ML technologies by focusing the A2I2 on rapidly advancing AI capabilities for movement and maneuver during MDO. A2I2 is an AI ecosystem consisting of the 1) ARL Open and Extended Campuses, 2) NSRL, 3) SUNet, 4) DREN, 5) ARL HPC, 6) AODR, 7) an assortment of AI software tools, and 8) interdisciplinary SMEs. The A2I2 vision is to develop and employ a suite of AI to provide intelligent systems that assist Soldiers in dynamic, uncertain, complex, contested, austere, and congested operational environments. The strategy is to develop teams that consist of 1) Army

AI/ML researchers from ARL, to include Open and Extended Campuses, 2) researchers from academia and industry, 3) interdisciplinary technical teams for collecting unique datasets for training and testing, 4) interdisciplinary teams, to include the user community, for planning and executing MDO-representative experiments in realistic environments, and 5) transition partners to field AI models to appropriate platforms.

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List of Symbols, Abbreviations, and Acronyms

3-D	three-dimensional
A2I2	US Army AI Innovation Institute
AI	artificial intelligence
AODR	Automated Online Data Repository
C4I	command, control, communication, computers, and intelligence
DAVC	Dynamically Allocated Virtual Clustering Management System
DOD	US Department of Defense
DREN	Defense Research and Engineering Network
DSRC	DOD Supercomputing Resource Center
FOV	field of view
GPS	global positioning system
HADR	Humanitarian Aid and Disaster Relief
HPC	High-Performance Computing
IR	infrared
ISR	intelligence, surveillance, and reconnaissance
MBT	main battle tank
MDO	Multi-Domain Operations
ML	machine learning
NSRC	Network Science Research Center
NSRL	Network Science Research Laboratory
R&D	research and development
RF	radio frequency
SME	subject matter expert
STEM	science, technology, engineering, and mathematics
SUNet	Secure Unclassified Network
SWaPT	size, weight, and power, time

S&T	science and technology
TRADOC	US Army Training and Doctrine Command
TTPs	tactics, techniques, and procedures

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