Collaborative Technology Alliances

Advanced Decision Architectures
Communications and Networks
Power and Energy
Advanced Sensors
Robotics

Capabilities for the Future Army

2003 Annual Report

Approved for public release; distribution is unlimited

Contents

A Message from the ARL Director (A) **3**

A Message from the Research Alliance Coordinator **5**

Overview of the Collaborative Technology Alliances **7**

CTAs Research Focus, Highlights, and Transitions

Advanced Decision Architectures (ADA) 11

Advanced Sensors 19

Communications and Networks (C&N) 27

Power and Energy (P&E) 33

Robotics 41

Appendices

Alliance Members 51

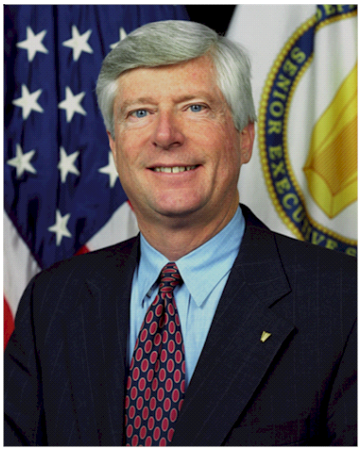
CTA Points of Contact 57

List of Acronyms 59

Intentionally left blank

A Message from the ARL Director (A)

Mr. John M. Miller



I am pleased and proud to present this Collaborative Technology Alliances (CTA) Annual Report documenting the past year's results of the collaboration among the U.S. Army Research Laboratory (ARL), industry and academia. The CTA encompasses the areas of Advanced Decision Architectures, Advanced Sensors, Communications & Networks, Power & Energy and Robotics.

Using technology to keep the Future Force the best army in the world, the five CTAs collective efforts successfully strive to overcome formidable challenges. A few highlights include:

- Used "shared displays" technology, enabling Soldiers to identify enemy targets and to indicate attack approaches, a technique under review for use in Iraq. (Advanced Decision Architectures Alliance)
- Developed, demonstrated and transitioned techniques to auto-configure network domains to the CERDEC Multi-functional On-the-move Secure Adaptive Integrated Communications (MOSAIC) Advanced Technology Demonstration. (Communications & Networks Alliance)
- Conducted research to develop more effective detection of freshly buried mines and improvised explosive devices using two-color long-wave infrared target detection. (Advanced Sensors Alliance)
- Developed, tested, and transitioned the technology to send vehicles on autonomous missions for reconnaissance, surveillance, targeting and acquisition to the Army's Autonomous Navigation System (ANS) program and TARDEC's Vetronics Technology Integration program. (Robotics Alliance)
- Demonstrated 1 & 2 watt Direct Methanol Fuel Cell (DMFC) breadboard systems, an essential first step in the development of a high energy-density power pack with potential five time increase in capacity over the present-day soldiers' battery pack. (Power & Energy Alliance)

Over $18M was placed on the CTA transitions contract by other agencies during 2003 to leverage our $34M core research program and to rapidly transition research products to Army applications. Other success indicators include:

- published over 400 refereed papers, conference presentations and proceedings
- supported 46 Post Doctoral researchers and 477 graduate students, with 31 Masters degrees and 25 PhD degrees completed
- accomplished 36 staff rotations into ARL and 11 staff rotations out of ARL to partner organizations, which significantly enhances collaboration
- conducted 33 workshops, seminars, and short courses

These are just a few examples of the accomplishments documented in this report. The CTA program will continue to push the development of technologies for the Future Force and to transition these technologies rapidly as they mature.

Intentionally left blank

A Message from the Research Alliance Coordinator

Dr. John W. Gowens

The past three years have seen steady progress in the research accomplishments of the five CTAs. Our results over the past year were extremely encouraging in support of the global challenges faced by the Army. One of the hallmarks of the CTAs and of its predecessor, the Federated Laboratory, is the belief that we can never be satisfied with our performance, and we must always aspire to what we have yet to achieve. The CTA collective drive to excel has again produced outstanding technology transitions toward ultimate deployment in the Future Force.

Advanced Decision Architectures produced a collaborative information exchange and knowledge sharing tool to promote team situational understanding on the battlefield. The tool, known as the Collaborative SLide ANnotation Tool (CSLANT) is currently being beta tested and holds great promise as a method to support collaboration to improve problem solving and decision making.

Power & Energy CTA research is helping to solve hybrid electric propulsion problems to enable the Future Force with a much smaller logistical footprint. An engineering model of a hybrid Silicon-Silicon Carbide (Si-SiC) switch module is being transitioned to the Combat Hybrid Power Systems (CHPS) System Integration Laboratory (SIL). This component will be integrated into CHPS inverter modules for testing under conditions relevant to the future force vehicles.

Robotics made advances in the underlying system architecture that will enable unmanned ground vehicles to exhibit collective and individual tactical behaviors associated with reconnaissance, surveillance, and target acquisition missions. In support of this architecture, they developed a single screen operator control unit for use in a High Mobility Multi-purpose Wheeled Vehicle (HMMWV) to provide both autonomous and direct control of robotic assets that includes a spoken language interface thus allowing the Soldier to guide the robot with verbal commands.

Advanced Sensors research on infrared target detection phenomenology led to the development of a two-color long-wave infrared camera. The camera is effective in identifying freshly buried mines and improvised explosive devices. This capability has the potential to have a tremendous impact on protecting our troops in the current conflict.

Communications & Networks made important strides toward the implementation of wireless *ad hoc* networks for the battlefield. Techniques were developed to configure network domains automatically without human intervention. This is a key step toward transit–ion to a future net centric force.

In the coming year, I am committed to building a collaborative team across the CTAs to better show the synergism of the five technology areas. This collaboration will leverage research from all the consortia to provide prototype demonstrations showing the value of a net centric force in the nontraditional combat situations the Army is currently facing while setting the goals for the Future Force. Combining research from communications and networks with advanced sensors deployed on an autonomous platform is an example of how the collaborative team will work together to illustrate the importance of CTA technologies to the Future Force.

The success of the CTAs remains as fresh today as when the partnering concept was first pioneered by the Army Research Laboratory in 1996. The potential for even greater impact on the Army in all the CTA technology areas lies ahead. Our responsibility and dedication continue to the Soldier on the battlefields worldwide. My CTA team and I will work every day to be worthy of their trust and sacrifice.

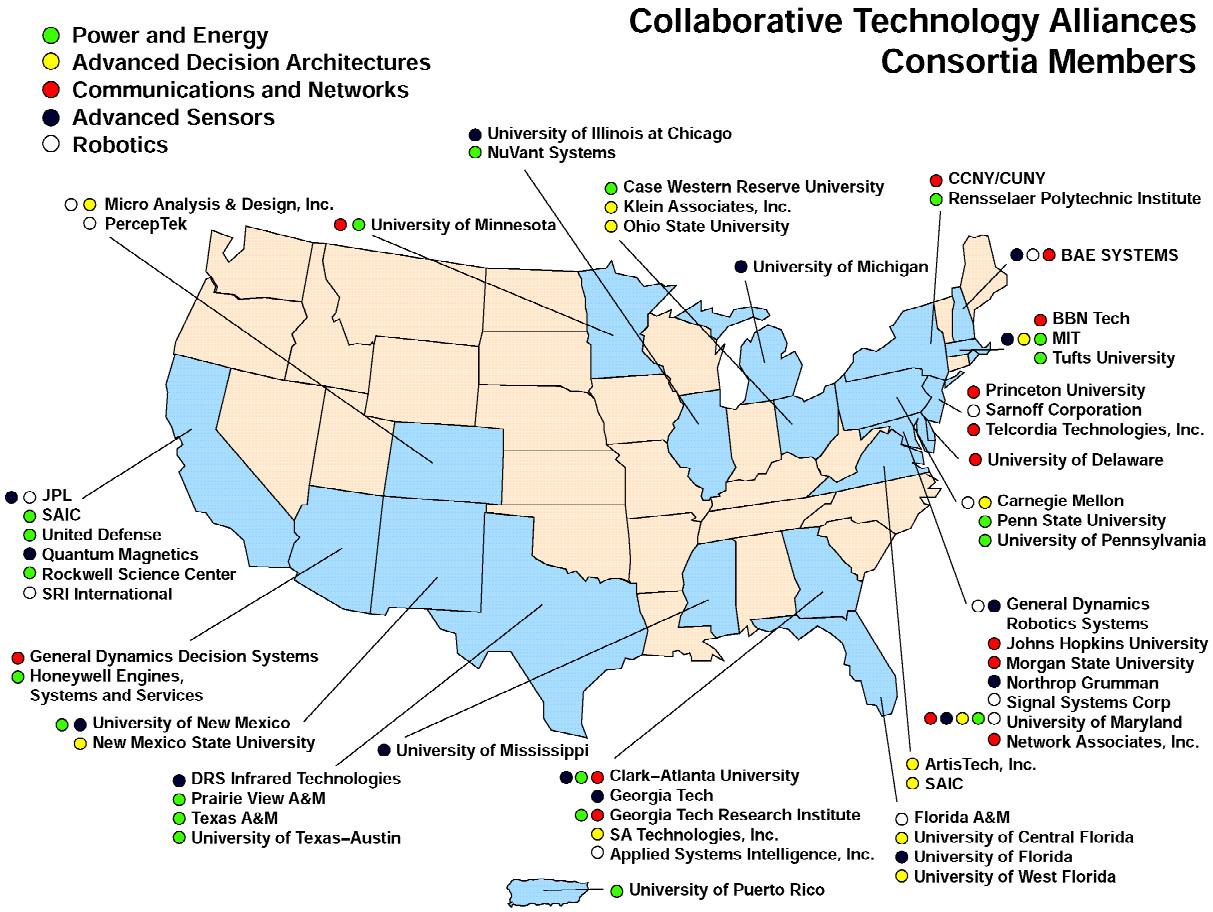
Intentionally left blank

Overview of the Collaborative Technology Alliances

In 2001, Cooperative Agreements were awarded to five consortia under the Army's Collaborative Technology Alliance (CTA) program in the following technical areas: Advanced Sensors, Communications and Networks, Power and Energy, Advanced Decision Architectures, and Robotics. The CTAs established partnerships among research communities in the Army Laboratories and Centers, private industry and academia.

Each alliance member brings with it a distinctly different approach to research: Academia is known for its cutting-edge innovation; the industrial partners are able to leverage existing research results for transition and to deal with technology bottlenecks; the Army Research Laboratory's (ARL) researchers keep the program oriented toward solving complex Army technology problems. Thus multidisciplinary research teams are generating the complex technology needed to solve the Army's complex problems. This approach enables the CTA program to bring together world class research and development talent and focus it on Army-specific technology objectives for application to Army Transformation.

The map shows the members of all five consortia and their locations. While all five consortia are managed and operated separately, they have a common set of management and program characteristics.



CTA member organizations.

Management structure. A Consortium Management Committee (CMC), which consists of leading individuals from member organizations, manages and governs the Consortium. Each member has one voting representative on the CMC to support programmatic and management-related activities and decisions. During regular quarterly meetings, the CMC decides all policy, business, financial, and technical issues of the Consortium, and represents the Consortium in reporting progress and transacting business with ARL. The CMC determines the membership of the Consortium, defines the tasks and goals of the partners, and determines the distribution of Agency funding to the partners. The CMC provides for ex officio representation by the CAM and other government personnel from other government agencies (OGA).

The consortium's research is organized into technical areas, each of which is led by an expert from an industrial member that has an established presence in that technology. To ensure that there is a close working relationship between the consortium and the Army, ARL has assigned a member of its staff to serve as a counterpart to each technical factor leader.

Research Management Boards (RMBs). The Alliances in the CTA program include not only the five consortia and ARL but also Army Research, Development and Engineering Centers (RDECs), other Army and other Government agencies (OGAs). The Army RDECs and OGAs are invited to actively participate in the research program and to conduct research jointly with Alliance members. The annual research program plan is also cooperatively formulated by Alliance members and ARL with input from the RDECs and OGAs through participation on the Research Management Boards (RMBs) established for each Alliance. The RMB partners are critical to identifying opportunities for transitioning CTA research results into their on-going R&D programs. This transition is facilitated by a task order contract built into the CTA agreements. Several Army RDECs and OGAs have taken advantage of this contract mechanism to apply CTA research results to their technology development programs.

Technology Transition. The CTA program's value to the warfighter is significantly enhanced when we exploit the full potential of the enabling technologies that result from the basic research projects. Our technology transition approach relies on collaboration and partnering of ARL, RDECs and RMB members. This team works with the technology user community to seek out transition opportunities and to demonstrate technologies mature enough for application. Our approach extends activities beyond research papers to matching technology with customers early and then jointly mapping the transition path with them. The identification of user champions through early and frequent collaborations and partnerships is a key component of our process for effective transition with defined entrance and exit criteria.

Leverage. CTA researchers participate in many key defense programs such as Future Combat Systems (FCS), Objective Force Warrior (OFW), Warfighter Information Network–Tactical (WIN-T), and Adaptive Joint Communications, Intelligence, Surveillance and Reconnaissance (CISR) Node (AJCN). Furthermore, each CTA member provides world-class laboratory facilities and testbeds for use by ARL and other CTA members. These facilities create tremendous leverage for the Army Science and Technology Programs.

Enhanced collaboration. Today's complex technology challenges have made it absolutely necessary to engage researchers on these multidisciplinary teams where new ideas can be successfully applied to complex Army problems. This is the Army's way of establishing a new research culture—transforming the old way of doing business—that fosters a different kind of relationship among research colleagues in industry, academia and Army laboratories and centers. As an integral part of the program, the CTAs use several venues through which such synergistic collaborations can be pursued and encouraged. Some of the venues used by the CTA program are summarized below:

- **Joint Research Projects**: The individual researchers collaborating on a particular research topic are involved in the planning at the task level, as well as in the execution of the overall research project. On many projects the researchers come from each of the three sectors—academia, government, and private industry—bring the advantages of a multidisciplinary approach to the research problem.

- **Staff Rotations**: The best example of collaboration is staff rotation, in which individuals temporarily relocate, if necessary, to work on a daily basis with the research group at a partner's organization. Such rotations may last months or years. The rotations produce mutual understanding of technical approaches and issues. The sharing of expertise among the participants foster new insights into difficult research problems and creates opportunities for advances not previously recognized before the exchange of personnel. In some cases the rotation is combined with a long-term training and educational component. This provides educational opportunities for graduate students from academia and staff scientists and engineers from the government and industry to earn advanced degrees and to perform cutting-edge research. The result is both individual and institutional associations that endure and grow to far exceed the separate capabilities.
- **Workshops**: Each technical area organizes focused workshops to discuss technical progress and challenges unique to that topic. This provides a forum for effective interaction between researchers from ARL, the participating consortium members, and Army RDECs.
- **Distinguished Lecture Series**: A monthly seminar is presented by an expert from one of the consortium partners or ARL to more broadly communicate the technical issues and progress on specific projects. Members of all CTA alliances are invited to attend either in person or via video teleconference.
- **Seminars and Short Courses**: More informal seminars and short courses are conducted frequently, and primarily involve members of a particular CTA or technical area. Certain seminars are specifically designed to address technical areas which include several CTAs and serve as starting points for cross-CTA collaborations. Short courses are developed for particular projects that cross multiple disciplines. In these cases, it is of particular benefit for researchers to gain more in-depth knowledge of all technical areas within the project, and an expert presents several days of technical material specifically designed for the purpose.
- **Annual Symposium**: The CTA program holds a symposium each spring to present the results of its research and describe plans for the next year. Program overviews, technical papers and posters, exhibits and demonstrations serve to communicate the research products of the CTA program to Army organizations and other Department of Defense agencies. The symposium fosters interactions and collaborations among researchers from all the technical areas and all the alliances.

From the cooperative program formulation through the collaborative research efforts, the CTA program is efficiently focusing the expertise of industry, academia and the Army Research Laboratory on enabling technologies and new military capabilities needed for Army Transformation.

Intentionally left blank

A Message from the Advanced Decision Architectures (ADA) Leads

Dr. Michael Strub (ARL)

Collaborative Alliance Manager

FY03 marked the entry of the Advanced Decision Architectures Collaborative Technology Alliance (ADA CTA) into the Battle Command Battle Lab (BCBL) experimentation program. Following months of careful planning, the Director of the Ft Leavenworth BCBL assumed the role of the Unit of Action (UA) commander in a research event which clarified the command & staff information needs and the decision-making process for the Future Force. One interesting result was the heavy use of the "pre-mortem" to be sure that the staff understood commander intent. This enabled the staff to respond to unexpected events requiring rapid action at a lower level of command than in prior military operations.

Ms. Susan Archer (Micro Analysis & Design, Inc.)

Consortium Program Manager

By combining the theories of how people make decisions with the emerging technologies being developed in this program, we can expect a significant jump in the ability of Army decision-makers to make the best decisions quickly with an understanding of the risks and opportunities associated with the possible courses of action. We anticipate that our work will enable us to 1) increase the bandwidth of human input and output and 2) provide information to humans in more intuitive and, therefore, easier to process ways. These technologies, properly applied, can multiply the effectiveness of the human decision-maker on the battlefield. Our alliance is focused on meeting this challenge in ways that will work in the Army's unique environment.

Advanced Decision Architectures Research Focus

ADA CTA research focuses on four main technical areas, with cross-collaboration between areas:

- ***Cognitive Process Modeling and Measurement***: In this technical area, partners are developing the concept of macrocognition to assist in understanding the decision-making requirements of Future Force commanders. Computational models of cognitive processes are laying a foundation for collaborative technologies and decision support systems. We are researching unobtrusive ways to quantitatively assess users' states to better support decision-making. Finally, to communicate their ideas and to assess their impact, researchers are developing and showcasing user-centered design methods to test in realistic Army scenarios.
- ***Analytical Tools for Collaborative Planning and Execution***: In this area, the partners are creating tools and intelligent systems that support collaborative decision-making across distributed teams, allowing decision-makers to share data in meaningful ways, and to examine the impact of their decisions. To accomplish this, we are conducting work to understand how individuals and teams make decisions, assess situations, and interact with technology. Also, researchers are prototyping and iteratively testing collaborative software-based tools with actual Army decision-makers. We are defining the characteristics of successful tools for collaborative decision-making, and we are developing the algorithms to support Army planning systems.

- ***User Adaptable Interfaces***: Ever since humans began using tools, we have intuitively recognized the value of adapting the interface between the tool and the human. The need for adaptive interfaces comes from differences in individual Soldiers, the Soldier's task, and the system. In this technical area, we are extending this long tradition of user adaptable interfaces into the world of decision-making architectures. This is being done by researching several specific topics including image stabilization, mobile agent technology, and multi-modal interfaces.
- ***Auto-Adaptive Information Presentation***: Going one step further down the path of interface adaptation is the ability of the user interface itself to automatically adapt to the changing needs of the user. There are risks associated with that in terms of changing things without the user knowing or desiring it. This technical area involves developing a strategy and technologies to better evaluate how auto-adaptive information presentation can support tactical decision-making. Research is being conducted to develop key principles and control algorithms for applying auto-adaptation such as keeping users informed of the "big picture," keeping users in the control loop, maintaining critical cues, and using auto-adaptation only when needed.

Advanced Decision Architectures Research Highlights

Technical Area (TA) 1: *Cognitive Process Modeling and Measurement*

Developing Conceptual Models of Cognition

ADA partners performed research to understand *intent* centric command and control by conducting a concept development experiment with the Battle Command Battle Lab at Fort Leavenworth, Kansas (BCBL-L). They examined an *intent* centric planning process as an alternative to plan centric decision-making. The payoff in this work is that understanding the cognition underlying *intent* centric planning will produce solutions that equip the Future Force commander to visualize, comprehend, decide, and communicate his concepts *to lead the force at the speed of thought.*

Computational Modeling

Our team has developed new modeling frameworks to assist in predicting total system performance, where a dominant aspect of the equation is the ability of the Soldier to make effective and timely decisions. These researchers developed new methods to predict learning and comprehension, situational awareness, high-fidelity cognitive performance, and expert decision-making. Once these software frameworks are validated, they can be used to impact system design, early in the acquisition process. Another payoff for this work is that it will lead to the development of intelligent agents that can be embedded in battlefield systems to assist Soldiers in their real-time decision-making.

Naturalistic Decision-Making

The ADA partners organized and led the Sixth International Conference on Naturalistic Decision-Making (NDM6), which was held in Pensacola, Florida on May 15-17, 2003, with joint agency sponsorship that was facilitated through the ARL ADA mechanism.

NDM6 brought together world leaders in the fields of cognitive engineering, human factors engineering, and experimental psychology, with representatives of the Army, Navy, Air Force, and National Aeronautics and Space Administration (NASA), and of the armed forces from other nations (i.e., Sweden, the United Kingdom). Cutting-edge work in the areas of Expertise Studies, Human Centered Computing, and the Psychology of Decision-Making was presented. As with previous NDM meetings (held every other year), the focus was on how practitioners in real-world domains of complexity achieve expertise and make decisions.

The resulting compendium of presentations encapsulates the latest advances in theory and research on certain aspects of military psychology and human engineering, aspects such as team collaboration, multinational operations, the psychology of intelligence analysis, and intelligent systems for decision-aiding.

Decision Centered Design

Decision centered design.

Our team developed display prototypes to show how Situational Awareness (SA) oriented design concepts can be implemented to support Army brigade officers as they seek to build and maintain the level of situational awareness needed to accomplish their mission. In conjunction with ARL, these display concepts were developed into an interactive exhibit to demonstrate how to support officers as they seek to build both individual and team SA. This demo will provide the testbed for further evaluation of design concepts for assisting brigade officers as they build SA in uncertain, information intensive battlefield environments.

Macrocognition

Work in this area focused on describing the connection of Decision-Centered Design (DCD) to the ongoing methods currently in use in the Army to determine operational requirements and potential solutions, as implemented in the Training and Doctrine Command (TRADOC) Battle Labs and especially in the Centers of Research for Future Combat Systems (FCS)/Objective Force Unit of Action and Unit of Employment (Fort Leavenworth and Fort Knox, respectively). This work resulted in recommendations on how DCD methods could contribute to existing methods for rapid prototyping and concept development.

Technical Area 2: Analytical Tools for Collaborative Planning and Execution

Collaboration and Effectiveness in Human Teamwork and Human-System Teamwork

ADA had several research projects in this area. The first investigated team processes and the development of common ground in Army exercises using newly developed team cognitive task analysis methods. In the second, team members tested and refined their model of team adaptability, specifically, how Soldiers cope with performing diverse or ambiguous missions. They have also begun to address the impact that multi-cultural team composition will have on team adaptability. Finally, we developed computational linguistic techniques (e.g., Latent Semantic Analysis) to predict individual and team level knowledge, based on communications. This work will result in more effective multinational coalition forces for Stability and Support Operations (SASO), focusing on understanding and assessing the impact of cultural differences. Collectively, these efforts crystallize the important teamwork competencies needed by the new Army, and will result in a tool kit for the assessment of team adaptability.

Tools to Support Collaboration and Decision Making in Collocated and Distributed Teams

ADA partners measured collaborative tool effectiveness during a BCBL experiment in order to identify the usefulness of collaborative tools for Future Force Command and Control (C2) organizations. In parallel, our team developed algorithms and tools to create new automated planning components in support of a larger FCS C2 system architecture. We also developed advanced decision support technology for information gathering and interpretation to support collaborative understanding and inferring ground truth from data. This combination of work defines the backbone architectures that will be needed to transfer and integrate various systems, sensors and information for display and use in real-time field operations.

Real-Time Battlefield Planning Tools

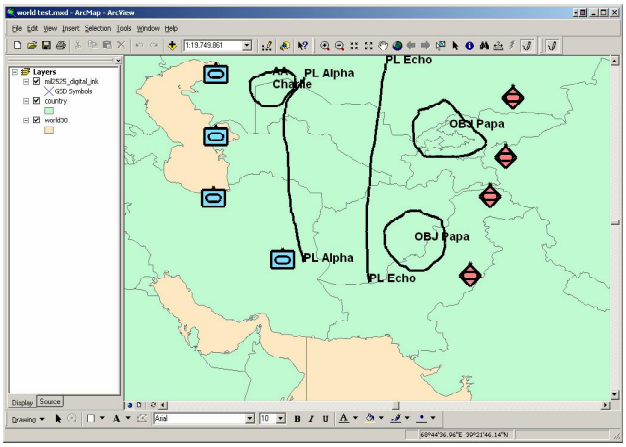
Real-time battlefield planning tools.

ADA partners developed the prototype Collaborative SLide ANnotation Tool (CSLANT) to provide a rich, asynchronous communication environment to support collaborative planning, decision-making, and dynamic replanning among military team members who may be distributed geographically as well as temporally. Using CSLANT, the context of the message is formed by taking a series of computer screen snapshots (e.g., from MCS, a COA sketch, etc.) and then annotating these images with synchronized voice and pointing, pen marks, text-based notes, arrow markers, and military symbols. This tool is currently being beta tested at various Army sites (e.g., 25th Infantry Division (ID), 1st Combat Division (1CD), U.S. Military Academy (USMA), etc.), and by ARL-Human Research and Engineering Directorate (HRED) and ARL-Computational and Information Sciences Directorate (CISD) personnel.

This work aligns with the Army's focus on the critical and essential nature of collaboration in Command and Control problem-solving and decision-making. The CSLANT prototype and the processes that it enables help to facilitate collaborative information exchange and knowledge sharing, promoting team situational understanding during planning and execution of operations between individuals at diverse locations and with different levels of skill and experience.

Technical Area 3: User Adaptable Interfaces

Diagrammatic Reasoning



Diagrammatic reasoning.

ADA researchers completed development of a framework for representing diagrams and using it as part of a problem-solving system for military situation assessment and planning. As part of this work, they implemented an algorithm for identifying groups and their lines of motion and demonstrated its effectiveness in constructing a motion diagram of Red forces in ARL-supplied data from an exercise at the National Training Center.

Displays for Situation Understanding

Our team performed research that indicated spatial displays that use depth cues will lead to distortions of the perception of the size, height, and speed as a function of the perceived depth of an object in the display. The distortions increase as the perceived depth increases. This research will be used in developing display design guidelines that will lead to more accurate design of displays for 3-dimensional information.

Also, ADA researchers conducted experiments to examine elements of visual perception, and the effects of risk visualizations on dynamic decision-making in a realistic missile resource allocation task. This context was chosen because it is essential that operators make nearly instantaneous decisions while maintaining good situational awareness. Their work provides a better understanding of how to represent uncertainty in visual displays in order to improve user situation understanding and decision-making performance.

Multi-modal Displays and Speech Interfaces

ADA built two haptic displays that will provide tactile cues to the torso of a Soldier to assist in navigation and threat location. One display is based on small electromagnetic motors mounted in a vest, and the other on contractile shape-memory alloy fibers. These systems provide the Army with a nonverbal, low signature means of communicating with the Soldier.

We integrated the Ariadne dialogue manager with multiple systems at ARL including Experimental Unmanned Vehicle (XUV). They improved the Ariadne dialogue manager robustness including reduced load time, support for large grammars, improvements in runtime, improved support for new grammars. With Ariadne, ARL is able to create prototype speech interfaces for their existing applications in as little as 6 hours.

Multicriterial Decision-Making

Our team developed and demonstrated a visual interface to view Course of Action (COA) simulations and develop insights about COA decision space, e.g., how predictive an intermediate goal or event is with respect to various COA performance measures. Additionally, they demonstrated multi-criterial COA selection capability that interoperates with other ARL-developed technologies for genetic algorithms-based COA generation, wargaming for COA simulation, and COA visualization.

Technical Area 4: Auto-Adaptive Information Presentation

Shared Displays

ADA researchers redesigned existing 2-D and 3-D visualization engines to introduce collaborative control mechanisms and to support a web-based thin client environment for those platforms where no (or extremely limited) graphic capabilities exist. The rendering algorithms and underlying data structures and representations were enhanced to support the multiple storage, compute and display capabilities intrinsic to the different platforms. The resulting prototype was demonstrated at Collaborative Technology Alliance Conference (CTAC) 2003 and was successfully used by Soldiers in the Warrior's Edge (WE) experiment in August of 2003 to identify enemy targets and to indicate attack approaches.

Multimodal Control of Unmanned Vehicles

Our researchers worked together to conduct experiments to examine the issues associated with different methods of controlling small, unmanned ground vehicles (e.g., joystick, voice) in limited bandwidth environments. Their results indicated a clear negative performance impact associated with frame rates less than 8 frames per second (fps), even in very simple navigation tasks in confined environments. This work, along with planned follow-on experiments, will provide designers with empirical evidence with which to conduct tradeoffs.

Dynamically Reconfigurable Software Agent Systems

We explored how agents and mobile code can be used in conjunction with autonomous vehicles in order to greatly improve the ability to task and reconfigure them in the field, and to enable them to interact seamlessly with humans as team players. They also addressed the security requirements that arise with mobile code systems. This work will enable FCS to be extremely flexible and adaptable to changing missions and environments.

Multimodal, Multi-agent Coordination

Our team expanded and fine-tuned its multimodal, computer-based simulation environment. We used it to complete the data collection for a first study to identify and analyze preferred patterns and strategies for selecting, combining, and switching between vision, audition, and touch for communication and coordination in simulated battlefield operations. Identifying, and assessing the effectiveness of preferred strategies for modality usage across operational contexts is critical for the design of a robust adaptive multimodal interface for future Army operations. This interface will help increase the effectiveness of information exchange among Army personnel and thus support distributed decision-making among units.

Multimodal, multi-agent coordination.

Human-Robot Coordination

ADA partners explored human-robot coordination strategies in the context of *shared perspective* issues. They used specific difficulties in remote perception (such as scale ambiguities; uncertainty in topology of explored space) as initial test cases to explore how to establish *functional presence* through new enhancements to video feeds that enable the perception of affordances in remotely sensed environments. The test cases were implemented as 3-D animated simulations of the visual feeds from a robot exploring a building and urban environment. The results can be used to help design future Soldier-robot teams. The new concepts for remote perception are particularly relevant to Military Operations Urban Terrain (MOUT) and using robots in confined spaces.

Recognizing and Communicating Events

Consistently, research finds that practitioners reason and interact in terms of event patterns. These events are based on relationships across data, across time, and relative to the background of expectations, planned activities, team structures, and goals. We focused on identifying methods for extracting meaning of an unfolding situation based on disparate data from multiple data sources that might be uncertain, incomplete, inaccurate, or outdated. This work will lead to tools that make event patterns a basic building block of visualization, collaboration, analysis, prediction, decision, and action.

Advanced Decision Architectures Technology Transitions

The ADA CTA has been awarded over 25 technology transition task orders. Selected highlights are summarized below:

- ***Warrior's Edge Support Through Shared Displays***: Under this task order, the Shared Displays prototype developed by ArtisTech in a TA4 research task and demonstrated at the CTAC 2003 was used in the Warrior's Edge (WE) experiment in August of 2003. In particular, the Digital Ink component was used directly by soldiers to identify enemy targets and to indicate attack approaches. This technology is currently under review for use in Iraq, for use at the Joint Forces Command Center (JFCOM) , and its role will be expanded in WE for August 2004 exercise. Furthermore, Digital Ink technology will be deployed in January 2004 as part of a larger INSCOM system.
- ***Decision Aids for Counter Terrorism, Counter Narcotics and Computer Network Operations***: Developed and fielded software tools with advanced visualization capabilities to enable intelligence analysts to collect and analyze data from multiple sources in order to quickly identify patterns that indicate terrorist or other illegal activity. These tools were transitioned to INSCOM.

- ***Extension of Control, and Communication Techniques for Reliable Assessment of Concepts (C3TRACE) in Support of Command and Control (C2) in Complex and Urban Terrain***: Packaged and fielded a user-friendly software tool to enable analysts to assess the impact of organizational structure and task allocation on the flow of information critical to support decision-making. This tool is being used by ARL to identify UA manpower and personnel issues.
- ***Improved Performance Research Integration Tool (IMPRINT) Version 8 for Manpower, Personnel and Training Integration (MANPRINT) Modeling***: Extended an existing human performance simulation tool to include state-of-the-art methods for predicting decisions Soldiers will make in combat environments. Also includes user-friendly capabilities to assess the impact of training on total system performance. IMPRINT is fielded to over 120 Government and contractor users to assist in the development of Future Force systems (e.g., FCS, OFW).
- ***Ground-Based Missile Defense Command and Control (GBMC2) Crew Situational Awareness and Decision-Making Capabilities***: Investigated the application of configural displays as a means to convey risk to operators in a realistic GBMC2 simulation environment. This effort resulted in user interface designs that will improve operator situational awareness and decision-making in high risk, time-constrained environments.

Intentionally left blank

A Message from the Advanced Sensors Leads

Dr. Dan Beekman (ARL)

Collaborative Alliance Manager

The CTA goal of innovative joint research is impressively demonstrated by members of the Advanced Sensors CTA team, with university and industrial scientists dynamically collaborating with their ARL colleagues. The basic research program has already generated many technology transfer projects that will provide specific deliverables of interest to Army customers, and on-going research promises further advances that will result in additional capabilities for Army warfighters.

Mr. Stephen M. Scalera (BAE Systems)

Consortium Program Manager

The Advanced Sensors Collaborative Technology Alliance (ASCTA) is a consortium of university and industrial laboratories that have come together to work with the ARL to drive technology towards the Army's vision for transformation into the Future Force. Our Advanced Sensors CTA program is focused on enabling "strategic dominance across the entire spectrum of operations" through technologies that provide: (1) unprecedented battlefield situational awareness and understanding; (2) accurate, all-weather, long-range identification and targeting for beyond line of sight engagement; and (3) a multi-function radio frequency (RF) capability for active RF sensing, countermeasures, and high-bandwidth secure point-to-point communications.

Advanced Sensors Research Focus

In order to achieve our research vision, the CTA advanced sensors research focuses on three technical areas:

- ***Microsensors, easily deployed and versatile***: Multi-modal microsensors will provide Soldiers with overmatching situational awareness, increasing their effectiveness and their survivability. Our Microsensor component and algorithm research will enable lighter, lower power, and highly effective microsensor components and algorithms for application to Soldier-worn, vehicle-mounted, and unattended sensors.
- ***Electro Optical (EO) Smart Sensors, the eyes of the future force***: Smart EO sensors provide the Soldiers with even greater capability to own the night. Our focused research into higher temperature focal plane arrays, 3-D imaging ladar (laser radar), and image fusion and automatic target recognition (ATR) processing will extend the spectral dominance, lower the cost, and increase the information collection capabilities of these sensors.
- ***Advanced RF Concepts, multi-function and compact***: Our research in new concepts for affordable electronically scanned antennas (ESAs) will enable Future Force platforms to acquire, target, counter, and communicate all through the same small set of distributed apertures. Materials and advanced device technology development will enable a whole new class of power efficient microcircuits with significant dual-use impact for military systems and commercial products.

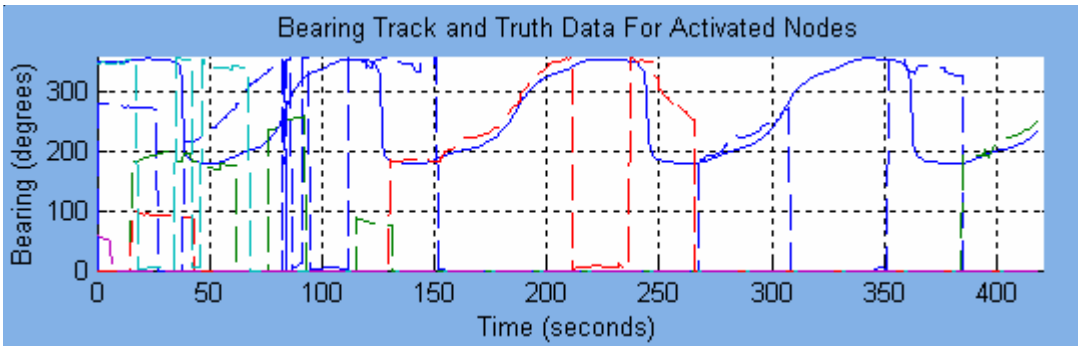
Advanced Sensors Research Highlights

Technical Area 1: *Microsensors*

An important challenge in obtaining dominant situational awareness on the battlefield is to detect multiple enemy targets in a variety of environmental conditions. One approach is to “fuse” information from different sensors types to accurately locate, track and identify targets. The following highlights show significant progress towards an integrated algorithm that fuses acoustic and infrared sensor information to detect, track and classify multiple enemy targets simultaneously.

Multi-Target Signal Discrimination and Classification Algorithms

BAE Systems investigated acoustic classification in a multi-target environment using short-duration signal estimation and feature extraction. We have analyzed the Micro Internetted Unattended Ground Sensor (MIUGS) and experimental array data collected during the 2002 Spesutie Island Experiment. Work was done closely with Georgia Tech and the University of Maryland toward combining multi-modal (tracking with acoustics plus imaging) information to improve target tracking and classification. The figure shows the track history of our existing single-node baseline for a M113/Heavy Expanded Mobility Tactical Truck (HEMTT) convoy. The tracks do not show any spatial discrimination between the two vehicles. We applied three different classification techniques to the data based respectively on the power spectral density, low-rank subspace tracking, and the Kolmogorov-Smirnov distance. The performance of each technique on independent time windows is encouraging and will improve dramatically as we take longer timeframes into account through a rule-based *M*-of-*N* voting scheme over multiple windows. Multi-target classification processing will be integrated in 2004 with particle-filter based acoustic processing, image sensor processing and with data fusion techniques to correlate clusters of target position estimates/tracks by associating similar feature measurements along a track.



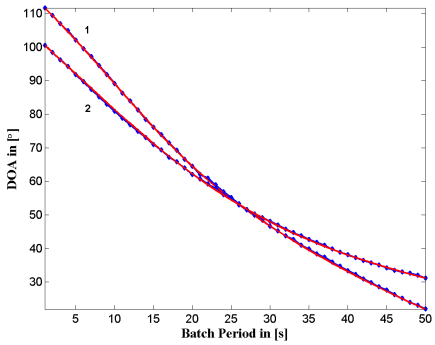
Tracking results at Red East for the Convoy clockwise run.

Target Tracking from Passive Acoustic Nodes

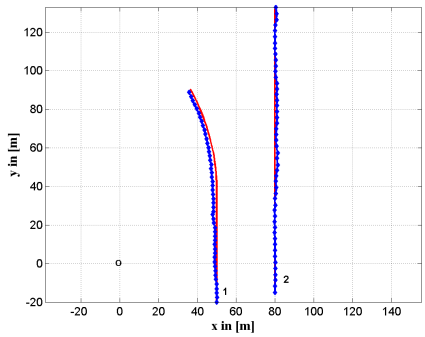
Passive acoustic arrays are used for covert tracking of targets. The independent partition particle filter (IPPF) is an algorithm employed by these arrays to calculate directions-of-arrival and then track multiple maneuvering targets. We have improved the performance of the IPPF by incorporating a time-varying frequency estimate of the targets into the filter. The new filter achieves superior tracking resolution that should enable the tracking of multiple targets in a convoy simultaneously by acoustic array.

In the figure, the sensor array is situated at the origin. Red lines are the true target tracks while the dotted blue lines are the particle filter estimates. Note that the two targets have directions-of-arrival that are normally considered unresolvable at their respective frequencies. However, since target #1 has a

different acoustic frequency from target #2, the modified IPPF algorithm accomplishes excellent tracking of the targets. Without the frequency modification, the regular IPPF would be unable to maintain tracks for these two targets.



Direction of Arrival (DOA) tracks calculated by the IPPF with frequency modification.



Actual and estimated target tracks from the particle filter.

Robust visual tracking algorithms realized with appearance-based models in a particle filter.

We have developed an approach that incorporates appearance-based models in a particle filter to realize robust visual tracking algorithms. Robust tracking needs models of inter-frame motion and appearance changes. In conventional tracking algorithms, the appearance model is either fixed or rapidly changing, and the motion model is simply a random walk with fixed noise variance. Also, the number of particles is typically fixed. All these factors make the visual tracker unstable. To stabilize the tracker, we added the following features: an observation model arising from an adaptive appearance model, an adaptive velocity motion model with adaptive noise variance, and an adaptive number of particles. The adaptive-velocity model is derived using a first-order linear predictor based on the appearance difference between the incoming observation and the previous particle configuration. Experimental results on tracking visual objects in long outdoor and indoor video sequences demonstrate the effectiveness and robustness of our tracking algorithm.

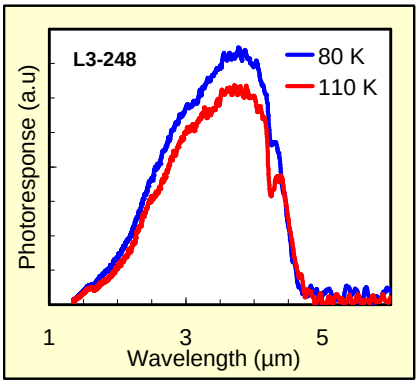
Frame 640 *Frame 670* *Frame 688*

Sample frames in a video sequence containing a moving vehicle. The appearance models are shown in the upper right corner and the tracking results are marked as the bounding boxes.

Technical Area 2: Smart EO Sensors

High Operating Temperature Detectors Based on InAs/GaSb Strain Layer Superlattices (SLS)

Higher operating temperature focal plane arrays (FPAs) will lead to lower system weight and longer life cryo-coolers for Army infrared imagers. Two approaches are being pursued: one is the more established mercury cadmium telluride material system and the other is relatively immature but very promising III-V materials technology in which the staggered (type II) band lineup of indium arsenide/gallium antimonide (InAs/GaSb) SLS is exploited to yield long cut-off wavelength. The SLS project is a joint task in which the University of New Mexico has optimized the InAs/GaSb SLS material and BAE Systems has developed processes which will lead to the fabrication of high quality and high uniformity detector arrays. University of New Mexico (UNM) has very recently grown high quality mid infrared detector material (4 µm wavelength). Single pixel detectors operating at a temperature of 110 K were fabricated using 100 periods of InAs/GaSb SLS as the active region. This followed a systematic study to optimize the structural, optical and electrical properties of the superlattice. Using a pseudopotential calculation, the band gap of the superlattice was determined to be 4.3 µm, which is in very good agreement with the experimentally obtained spectral response data shown at right. A peak detectivity of 5×10^{10}cmHz^{½}/W was measured at 78 K at ARL, which is an excellent indicator of improved material quality. Due to this important materials breakthrough UNM and ARL will provide optimized material to BAE Systems for the fabrication of 8×8 and 32×32 FPAs in 2004.



Spectral response from a 100 period InAs/GaSb SLS detector.

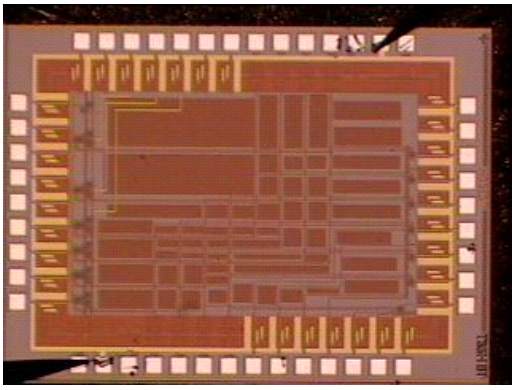
High Yield GaAs Detector Arrays Integrated with Capacitors for Ladar Imagers

The goal of this task is to integrate a mid-wave infrared (MWIR) or a long-wave infrared (LWIR) quantum well infrared photoconductor (QWIP) for passive imaging and a metal-semiconductor-metal (MSM) detector/mixer for eye-safe laser radar (ladar) active imaging. This integrated system will be a multi-band sensor that operates in the 1.5 µm eye safe spectral region and simultaneously performs conventional passive infrared imaging in either the MWIR or LWIR. Our approach leads to significant operational advantages:

- same field of view in both passive and active modes
- no scanning required for active sensing as the approach uses a staring infrared sensor for 3-D detection
- requirements for pointing accuracy and stabilization for both the sensor and source are reduced
- automatic bore-sighting capability by combining the passive and active sensors on a single detector array
- conventional passive infrared imaging occurs simultaneously with active 3-D imaging.

A mask design for such an integrated device was developed, and a process flowchart designed which will overcome the challenges of producing such an integrated device. Capacitor-integrated 32×32 MSM detector arrays were fabricated which also provide mixing functions. The detectors were highly uniform, evidenced by the data shown in the figure. These arrays will allow this novel ladar architecture to have higher performance at lower size, weight, and cost compared to other 3-D imaging concepts. Such a system would enhance the situational awareness of the battle space for Future Force ground systems.

First Generation Two Dimensional Readout IC for Active Imaging

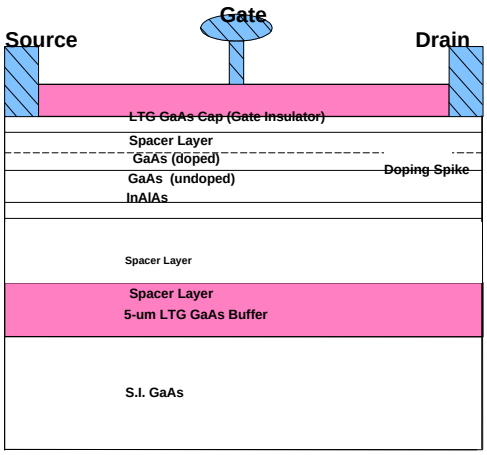


Active pixel test chip for 2-D ladar imaging.

We have designed and fabricated two dimensional (2-D) readout integrated circuit (ROIC) test chips for active laser radar (ladar) imaging systems. The ROICs are needed in order to maximize sensor performance, maintain a small footprint, achieve low power dissipation and enable large-format arrays. The 2-D active ROIC will enable assembly of a large-format ladar focal plane array via flip-chip bonding of an MSM array. The readout circuits employ a pseudorandom noise code readout technique that is compatible with existing ARL 2-D ladar processing and characterization hardware. The fully scalable pixel-size test cells contain cross-coupled switching gates for encoding, and virtual ground input current buffers to maintain proper biasing for MSM elements and for isolation. Some pixel cells also contain a differencing amplifier circuit behind the buffers to reduce clock feed through noise and chip area. The test chip meets the specifications regarding input impedance and it provides near-zero detector bias. Development of high-speed ROICs for ladar imagery is the first step in the process of creating a dual-mode passive/active imager on a single chip that would significantly enhance the range of detection and identification of targets while reducing the weight and cost of the sensor package for Future Force ground systems.

Technical Area 3: Advanced RF Concepts

Low Temperature Growth (LTG) GaAs Switch Device



Layer structure of a LTG-GaAs insulated-gate PHEMT.

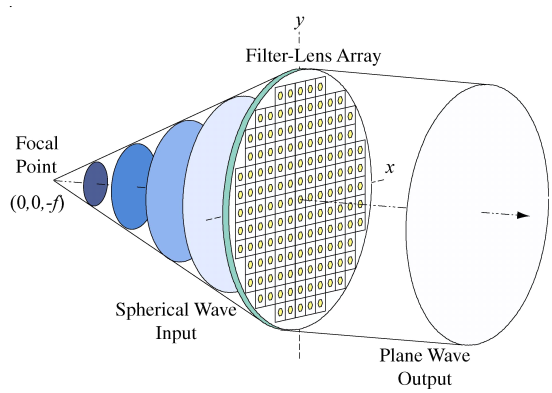
Current gallium arsenide (GaAs) transistor-switch technology is limited in its ability to provide very low-loss transistors with high-power-handling capability. The lack of a native oxide, suitable for fabricating insulated-gate metal oxide semiconductor (MOS) devices, is a major factor in the limitations of these transistor switches. This work has successfully demonstrated the first generation of a novel switch device which utilizes LTG GaAs molecular beam epitaxy (MBE) material inserted as the gate-insulator-layer of a high-performance pseudomorphic high electron mobility transistor (PHEMT). The result is a GaAs equivalent of a MOS-type PHEMT switch device usable through 40 Gigahertz (GHz) frequencies. When contrasted with a conventional PHEMT, the LTG-GaAs PHEMT device exhibited increased isolation between the gate and the conducting channel resulting in a two fold increase in the device breakdown voltage. In addition, its maximum forward-bias voltage increased from ~0.6 volts to 2-3 volts, thereby acting to reduce the channel resistance by up to a factor of two. In the next iteration of device fabrication, the ohmic contact resistance will be lowered with ion-implanted ohmic contacts, which are expected to lower the device on-state resistance from 1.6 ohm-mm to less than 0.5 ohm-mm. Once optimized, LTG-GaAs insulated-gate PHEMT technology will offer the potential for very low-loss, high power-handling switches suitable for operation through frequencies up to 40 GHz and be completely compatible with existing GaAs monolithic microwave integrated circuit (MMIC) fabrication lines. This low-loss switch technology promises to minimize costly amplifying components in electronically scanned antennas, enabling affordable multifunction radar systems for Army FCS vehicles.

Electron Channel Velocity Determined for Gallium Nitride HEMT Devices

Gallium Nitride (GaN) HEMT's are the only solid state amplifying device capable of substantial power levels at millimeter wave (MMW) frequencies. Such devices will have substantial impact on Army communications and radar systems by providing compact, efficient power sources and high dynamic range receiver front ends. This project has focused on obtaining higher frequency devices by optimizing the average electron transit velocity. Devices fabricated at Cornell University were tested with femto-second optical pulse/probe methods at ARL. Velocities in the usual GaN HEMT was determined to be 1.0×10^7 cm/s. Using a 1.5 nm aluminum nitride barrier above the channel to prevent real-space transfer, the velocity was increased by a modest 15%. Recent studies have confirmed that electron velocity is limited by the substantial build up of longitudinal optical phonons, an intrinsic characteristic of GaN. In 2004 we will pursue other more promising approaches to improve device performance including using special gate extensions (field plates), where it will be possible to operate at twice the usual HEMT drain voltage, thus allowing higher power and efficiency at frequencies of 40 GHz and above.

Novel Millimeter Wave Lens-Filter Array (FLA)

The filter lens-array is a novel multi-function component which can replace the dielectric lens in power combining, focal plane scanning, and millimeter-wave imaging systems. FLA, which is formed as a non-uniform array of antenna-filter-antenna elements, can be considered as the combination of a focusing array and a band pass filter. A 3 inch FLA was designed and fabricated using a standard thin-film process suitable for low cost manufacturing. The measured focusing gain of this FLA is 11 dB at 35 GHz, the 3 dB bandwidth is 8.2%, and the combined efficiency is 40–50%. This is similar to a Teflon lens and has much lower loss than the combination of the lens and band pass filter. The two-dimensional scanning performance of the FLA has been demonstrated for ±30° in the H-plane and ±20° in the E-plane. The FLA antenna architecture is a promising approach to efficient, compact and affordable scanning antennas for multifunction RF systems on Army FCS vehicles.



Filter lens array beam former.

Advanced Sensors Transitions

Examples of this year's technology transition activities are given below:

Long Wave Infrared (LWIR) Focal Plane Arrays for Mine Detection

The detection and neutralization of buried land mines is one of the Army's most difficult problems. These mines present a serious danger to civilian populations for many years after the conflicts are over. An airborne system that can remotely detect the presence of minefields and/or individual mines would be a very useful tool to cue other confirmation sensors. The ARL, in collaboration with BAE Systems, has demonstrated the use of two-color LWIR/LWIR infrared imagery for the detection of freshly buried mines. An airborne field experiment was performed in 2003 by ARL in conjunction with NVESD using a BAE Systems fabricated two-color 256 x 256 LWIR/LWIR focal plane array (FPA) detector. This two-color FPA was pixel-registered with simultaneous acquisition of both colors. Preliminary data gathering at CERDEC/NVESD demonstrated that two-color LWIR/LWIR imagery is effective in detecting freshly buried mines. Ultimately, this technology will be transitioned into the Lightweight Airborne Minefield Detection (LAMD) at NVESD. In 2002-2003 the development and the delivery of these two-color FPAs has been a significant technology transfer of the CTA program.

Development of a Disposable Sensor System

BAE Systems was awarded a task order contract to develop a disposable sensor system. The approach will focus on use of: acoustic, seismic, and possibly infrared motion detection transducers and their associated threat detection algorithms. These sensors were selected because of their threat detection utility and their very low cost consistent with the Disposal Sensor goals. These sensor modalities should be effective for threat scenarios including:

- Personnel passing in indoor stairwells and corridors
- Indoor human activity
- Vehicle activity
- Weapons fire in indoor and outdoor environments
- Operating machinery.

This work leverages the Disposable Sensor task initiated in FY03 and supports ARL technology transition to CERDEC/NVESD.

Ka-band (27–40 GHz) MHEMT MMIC Development

BAE SYSTEMS has executed a development cycle for metamorphic high electron mobility transistor (MHEMT) MMIC devices targeted at future Army multifunction apertures operating within a nominal frequency range of 37–40 GHz. A variety of MMIC types were fabricated including all transmit/receive (T/R) functions (power amplifier, low noise amplifier, switch, and phase shifter), thereby allowing high levels of integration to be achieved in the future. State-of-the-art Ka-band performance was achieved on several of these designs:

- High Efficiency Power Amplifier—demonstrated 1.5 W with 37% power-added efficiency at 38 GHz;
- Digital Variable Gain Amplifier—first pass success amplifiers exhibits over 15 dB of gain control range;
- Driver Amplifiers—first pass success of 150 mW and 250 mW driver amplifiers have also been demonstrated with excellent RF performance.

Eight different MMIC types, a total of 41 Ka-band MHEMT MMIC chips, were delivered to ARL on July 28, 2003. These devices are the basis for multifunction MMICs that will be employed in MMW electronically scanned antennas on Army FCS vehicles.

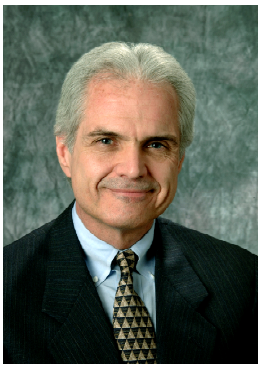
Intentionally left blank

A Message from the Communications and Networks (C&N)

Mr. Greg Cirincione **(ARL)**

Collaborative Alliance Manager

The Future Force will depend and exploit mobile, adaptable, and secure communication networks to enhance its survivability and lethality. This CTA teams leading government and private sector researchers, and focuses them on the most difficult challenges facing the Army as it migrates to a Future Force engaged in network-centric warfare. I strive to nurture and cultivate a collaborative environment that produces exciting and relevant research results that can have an impact. My goal is to transition and exploit this research to enhance warfighter capabilities for the Current and Future Force.



Dr. Ken Young **(Telcordia Technologies, Inc.)**

Consortium Program Manager

The research vision of the consortium is to develop technologies that enable a fully mobile, fully communicating, agile, situation-aware, and survivable lightweight Army force with internetted Command, Control, Communications, Computers, Intelligence, Surveillance and Reconaissance (C4ISR) systems. In parallel with the research program, we actively seek opportunities to transition the fruits of this research to programs that are laying the foundation for the Army's vision of network-centric warfare. The combination of leading-edge academic research and focused industrial research and development provided an environment where key technologies are beginning to transition into critical Army programs.

Communications & Networks Research Focus

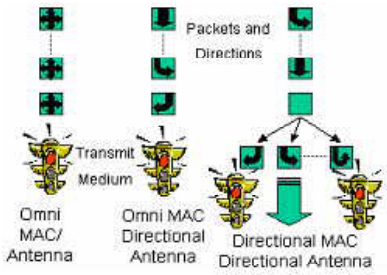
The goal of this program is to develop the underpinnings for the Future Force's communication network infrastructure. The focus is on technologies that: provide high data rate communications that is ***hard for the enemy to detect or intercept***; ***enable the network to be very dynamic and survivable despite unpredictable events such as network element movement, failure, or destruction due to enemy action;*** automatically configure protocols so that ***mobile networks can be quickly and flexibly deployed***; and ***efficiently protect the wireless mobile ad hoc network*** without reliance on strategic services. To achieve this, the CTA C&N research is focused as follows:

- ***Survivable Wireless Mobile Networks***: develops technologies that ensure that tactical networks are self-configuring and self-maintaining, highly mobile, survivable, scalable, energy-efficient, and interoperable with joint and coalition forces.
- ***Signal Processing for On-the-Move Communications***: develops technologies, focusing primarily on the physical and media-access layers of the communications protocol stack, to ensure efficient multi-user communications-on-the-move.
- ***Secure Jam-Resistant Communications***: develops waveform signal processing technologies that ensure reliable communications in environments containing significant interference generated from within the network and by hostile interferers.
- ***Tactical Information Protection***: develops technologies that provide automated, efficient, adaptive, and secure information protection in wireless, multi-hop, self-configuring networks.

Communications & Networks Research Highlights

Technical Area 1: Survivable Wireless Mobile Networks

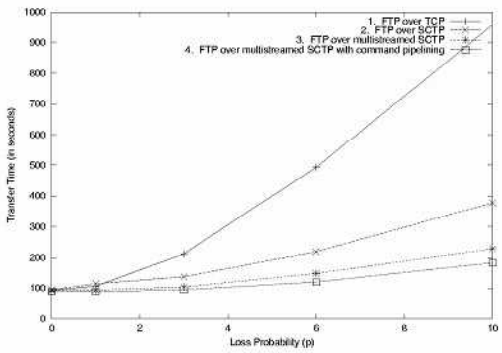
High-Throughput Medium Access Control for Sensor Networks with Directional Antennas



Improved performance with directional antenna and MAC.

Directional (as opposed to omni-directional) antennas (DAs) provide significant increases in throughput, covertness, and anti-jamming qualities, while simultaneously consuming less energy. Unattended wireless networked sensors must rely on such characteristics to compensate for their inability to move and to be capable of prolonged deployment, as well as stealth operation. The full potential of DAs can only be realized by networking protocols, and in particular medium access control (MAC) protocols, that are specifically designed for such antennas. Traditional contention-based MACs, designed for omni-directional antennas, often unnecessarily restrict transmissions that could be performed by a directional antenna without compromising other on-going communications. We designed a mechanism for DA MACs that considers the transmission direction of waiting packets and schedules transmissions to avoid conflicts with other nodes and maximizes the throughput of the entire sensor system. This mechanism has been shown analytically to significantly improve achievable throughput—asymptotically it improves by 66% as the degree of a node increases (as the density of the network increases).

Improving File Transfers in Mobile Networks Using End-to-End Multistreaming



Improved file transfer rates with multistreaming.

The ability to transfer files in mobile *ad hoc* networks, where end-to-end connections are often interrupted due to mobility and link failure, is currently inadequate. To improve mobile network performance, an emerging advanced transport protocol—the Stream Control Transmission Protocol (SCTP), a recently proposed Internet Engineering Task Force transport layer alternative—has been investigated and extended. For file transfers, a novel service of SCTP, multistreaming (allowing multiple independent streams per end-to-end communication) is exploited to reduce the overheads associated with the File Transfer Protocol (FTP). Multistreaming mitigates deficiencies in using Transmission Control Protocol (TCP) over which FTP runs, in particular the separate connections for data and control, non-persistence of the data connections, and the sequential nature of command exchanges. We modified FTP to use SCTP's multi-streamed service to avoid the identified TCP overheads without introducing complexity at the application. We experimented with various ways to implement FTP over SCTP and compared them with FTP over TCP. The figure shows the total time to transfer ten 1 Mb files over a 1 Mbps link with a 35 ms one-way delay for various link loss probabilities. We found that an approach using a single multi-streamed SCTP association for control and all data transfers with batching of multiple commands (command pipelining) provided the best performance, transferring files 2 to 5 times faster than TCP, while being significantly more robust to loss.

Dynamic and Survivable Server Pooling

Mobile tactical networks will require that distributed information servers and network infrastructure services (i.e., name servers, mobility support, etc.) be forward-deployed and subject to the effects of mobility and hostile actions. Guaranteeing the survivability and availability of these critical servers is difficult in a wireless mobile environment. We developed and demonstrated an approach to improving the survivability of such services. Called Dynamic Survivable Server Pooling (DSSP), it makes use of a pool of servers to improve service availability. The key underlying technology is a virtual backbone (VB) for *ad-hoc* networks that provides efficient service registration and name resolution for the server pool. The VB approach has the following desirable characteristics: (1) reorganizes itself in responses to mobility, failures, and partitioning (2) offers fast response time via locally-scoped query resolution (3) scales well as networks grow in size (4) is simple enough to be deployed on resource-constrained nodes (5) enables distributed server selection modeled as policy-based resource allocation. Through simulations, we have shown that our incremental improvements reduce unnecessary deregistrations by 66%-100% and the overhead for finding servers is reduced by 22% over existing approaches. We anticipate that in FY2004 the DSSP over virtual backbone approach will produce even more impressive performance figures.

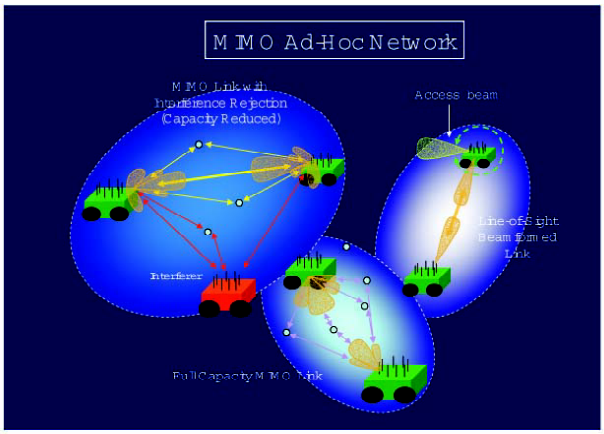
Technical Area 2: Signal Processing for Communications-on-the-Move

Multiple Access Techniques

In future Army wireless networks, it is critical for radio nodes to work together efficiently, minimizing multiple access interference. Multiple Access research develops waveform design and multi-user detection methods to maximize the number of Soldiers that can be supported with limited spectral resources. In pushing the envelope of signal processing methods to achieve a high degree of multiple access, this task seeks solutions characterized by low complexity and high performance. Key highlights include:

- The Army's operating environment requires high diversity, low power communications in fading channels to ensure continued communications even in the most difficult of conditions. We developed methods to realize this by employing multiple transmit and receive antennas and joint optimization of transmitter powers and waveforms. Theoretical analysis and extensive simulations indicate that our approach will yield a normalized mean square error improvement of 1.5 decibel (dB) to 6.5 dB over the current state-of-the-art.
- Low complexity solutions lead to lower development costs, lower power consumption and ultimately lighter equipment for the Soldier. We investigated novel signal processing methods to achieve low complexity solutions without incurring significant performance loss by recirculation of "soft" information in the radio receiver.
- Jamming of communications signals can result in a 20–30 dB degradation of the signal-to-noise ratio. We explored new multi-carrier solutions to facilitate anti-jam communications by exploiting jamming state information as well as adaptive antenna arrays. Using a technique called "hard decision coding", the effect of jamming is reduced to only 2 dB to 3dB.

MIMO Systems



MIMO ad-hoc network.

Multi-Input Multi-Output (MIMO) Systems research develops the signal processing methods required to support high-density, high spectral efficiency communications for Soldiers on-the-move. During FY03, the MIMO Systems task made substantial strides in both advancing the state-of-the-art and in over-the-air demonstration of high performance waveforms and signal processing techniques. Experiments include line-of-sight (LOS) and non-LOS scenarios, and high (10–40 Mega bytes per second (Mbps)), mid and low communication bit rates. Key highlights from FY03 include:

- We demonstrated a technique called Turbo-MIMO in over-the-air experiments using our MIMO testbed. The demonstrations showed how future Army radio systems will be able to achieve extremely high spectral efficiency in multi-user environments at low signal-to-noise ratios.
- We developed novel signal processing methods and Medium Access Control (MAC) schemes for MIMO systems, allowing dense networks of future MIMO nodes to optimally exploit the limited available spectrum, while adapting to time-varying resources in an infrastructure free network-on-the-move.

We proposed techniques to reap the maximum diversity afforded by the channel in the dimensions of space, time and frequency to facilitate low power communications.

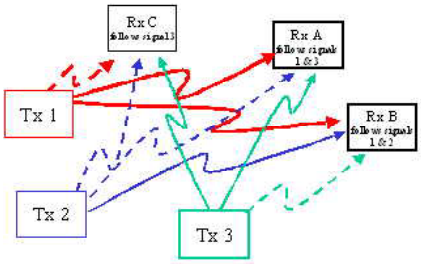
Technical Area 3: *Secure Anti-Jam Communications*

Channel Impairment Effects on LPI Waveform Performance

Future Army wireless networks demand low probability of interception and detection (LPI/LPD) in mission critical applications.

A primary obstacle is the mobile tactical wireless channel, which includes time-varying multipath effects, jamming, and multi-user interference. Research in this area hinges on appropriate channel models, realistically reflecting these conditions. Successful modeling techniques will lead to new and optimal communications signal processing schemes. The work is particularly relevant to design and development of mobile *ad-hoc*, sensor networks for battlefield communications operations. Along these lines, we developed mobile-to-mobile channel impairment models and evaluated their impact on channel estimation algorithms for Multiple Input Multiple Output Orthogonal Frequency Division Multiplexing (MIMO-OFDM) systems in jamming. These new models reflect motion at both the transmitter and receiver, adding realism over typical cellular models that assume one of the radios is not moving. Both theory and fast simulation modeling techniques have been developed.

Multi-carrier Modulation for Anti-Jam and Spectral Efficiency



Survivable communications using FFH-OFDM.

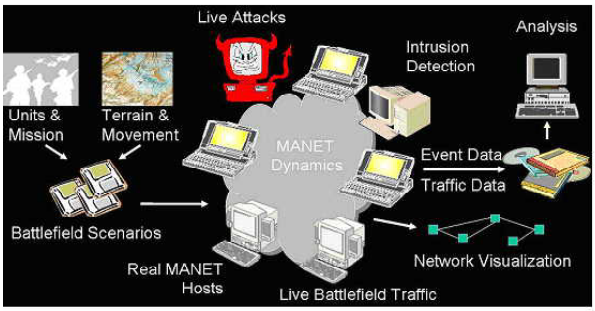
While there is a vast amount of research dealing with signal acquisition/synchronization and high capacity wireless transmission, few methods adequately address the Army's hostile channel environments encountered in the battlefield. Increasing capacity, while encountering malicious jamming and interference, is critical to minimizing *ad hoc* network manned-mission risk and improving the potential lethality of robotic- and sensor-based mobile networking. Generally, non-cooperative approaches, where no channel state is available, favor frequency hopping (FH) because of the difficulty in obtaining jammer/channel state feedback information. For information dominance, all transmission methods will require relatively high capacity to achieve timely command and control of the battlefield. We provide a scalable multi-carrier modulation solution using fast frequency hopping (FFH-OFDM) where spreading, survivable adaptive modulation, adaptive filtering, excision for anti-jam effectiveness, and high spectral efficiency are used for improved capacity. We studied joint preamble and embedded methods to improve the synchronization robustness for increased performance under high hop rates. We also addressed the carrier frequency offset and peak to average power problems.

Technical Area 4: Tactical Information Protection

Compression of Intrusion Detection Data With Known Error Bounds

Intrusion detection in bandwidth-constrained mobile *ad hoc* networks must operate on partial data due to the lack of concentration points where traffic can be analyzed. We developed an efficient means to transfer large amounts of attack monitoring data between nodes through the extension of multi-dimensional wavelet compression algorithms and a greedy optimization algorithm. This approach provides adaptive compression based on bandwidth constraints and accuracy guarantees required by intrusion detection algorithms. This approach demonstrates improvements in all error metrics (sum squared, absolute and relative error) and exhibits small memory/processing requirements.

Tactical Environment Assurance Laboratory

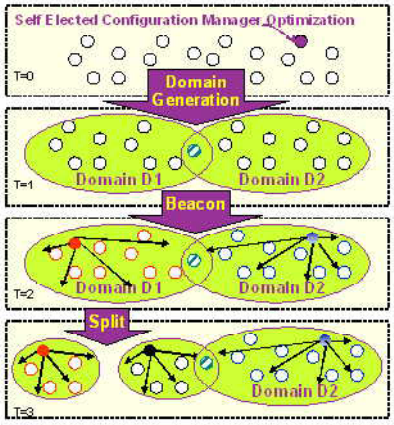


TEALab components and capabilities.

We established a Tactical Environment Assurance Laboratory (TEALab) with the objective to acquire a basic understanding of the characteristics of networking protocol and system attack manifestations in mobile *ad hoc* environments and provide experimental data to other research efforts. TEALab uses Mobile *Ad-Hoc* Network (MANET) technologies that have been demonstrated in tactical environments and emulates their mobility under various scenarios. This provides the Army with a new capability to study actual MANET protocol stacks and hosts using communicating battlefield applications as they are subjected to live attacks. It also allows insitu study of attack prevention and detection mechanisms, particularly regarding their resource demands, effectiveness, and ability to accommodate dynamic battlefield networking conditions.

Communications & Networks Technology Transitions

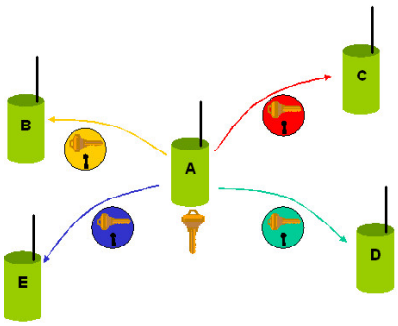
Domain Autoconfiguration for Mobile *Ad-Hoc* Networks



Domain autoconfiguration for mobile ad-hoc networks.

Future battlefield networks must configure and reconfigure themselves automatically as they adapt to the dynamics of ongoing missions. Dividing these networks into separate domains improves performance, especially for large networks. Domains allow routing, quality-of-service, mobility management and other protocols to operate on fewer nodes, with cross-domain interaction only through aggregated information. Without fixed points of reference, however, domain autoconfiguration is challenging in dynamic networks, needing both: a) fast response to minimize the disconnect time when networks split or merge, and b) global optimization to prevent creating inefficient or fragile networks. We developed a new modified simulated annealing algorithm that can divide 200 nodes into near-optimal (as defined by novel cost functions) domains in 2 seconds. The new algorithm is based on a cooling schedule, state transition probabilities and stop criteria tuned to domains. The team also designed and simulated a complementary beacon protocol that quickly identifies when networks split and merge. The beacon protocol and approaches to domain formation and re-formation are being transitioned to the CERDEC Multi-functional On-the-move Secure Adaptive Integrated Communications (MOSAIC) ATD for its 2004 demonstration.

Self-Authenticating and Bandwidth-Efficient Key Management Protocols



Identity-based group key management.

We integrated identity-based key management protocols into two technology transition projects: CERDEC's Tactical Wireless Network Assurance (TWNA) Science and Technology Objective (STO) and ARL's Blue Sensor Network Radio that is part of the Networked Sensor for the Future Force ATD. These protocols are self-authenticating and thus significantly reduce (by as much as ten times) the energy and latency costs versus existing certificate-based approaches. A new messaging approach was designed to accommodate these key management protocols. The existing messaging approach was also modified to provide encryption and message authentication using established keys and mechanisms, and to provide revocation of compromised keys. These protocols were designed, implemented and demonstrated for the TWNA STO.

Autoconfigured Mobility Management for Mobile *Ad-Hoc* Networks

Current mobility solutions such as Mobile IP (MIP), Session Initiation Protocol (SIP) and Dynamic Domain Name Service (DDNS) rely on fixed (i.e., non-mobile) servers. In battlefield networks, all nodes, including servers, are mobile. Thus, servers and relationships among servers should be autoconfigured. Using the concept of logical names and domains, we created a new scalable and efficient method of locating any node, user or server. In 2003 we merged the location and mobility management functions into a single Logical Name System (LNS). LNS servers are now optimally configured and maintained using the domain autoconfiguration system (see above) and a logical domain is automatically created among them using either network or application multicast trees. An analytical framework was used to objectively compare the many location management solutions. We used this model to compare MIP version 4 and MIP version 6. This analysis is planned to be used for the IPv6 analysis for CERDEC's MOSAIC and FCS projects. It has received interest from members of the Internet Engineering Task Force.

A Message from the Power and Energy (P&E) Leads

Mr. John Hopkins (ARL)

Collaborative Alliance Manager

Power & Energy technologies are pervasive, enabling and critical for transforming the Army. The technologies associated with Power Generation, and Power Control and Distribution, technologies addressed by the Power & Energy CTA, directly impact the operations of all Army and Department of Defense (DoD) elements.

Success in these technologies is critical in helping the Army meet operational and performance goals within the Future Force Warrior, Future Combat System and the Future Army.

Dr. Mukund Acharya (Honeywell Engines, Systems & Services)

Consortium Program Manager

Consortium research objectives will advance the fundamental science and understanding of efficient compact power and propulsion technologies needed to develop affordable, state-of-the-art systems required by the Future Force. To meet the Army's vision, compact and efficient power and propulsion systems are required to assure a survivable, affordable air-insertable, sustainable combat force with a small logistical footprint. The Consortium is focused on increasing the energy density of Soldier portable power systems by 5–10 times over current levels, and of vehicle propulsion systems by 3–5 times over current diesel engines, while reducing usage of fossil fuel by 75%.

Power & Energy Research Focus

In order to achieve our research objectives, the Power & Energy CTA research focuses on three technical areas:

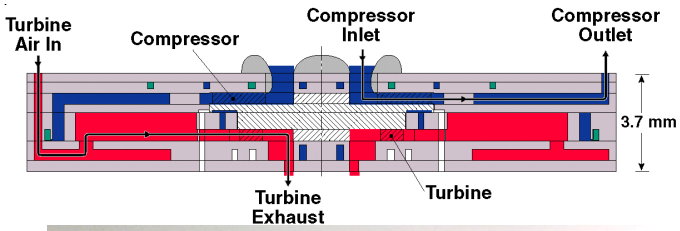
- ***Portable, Compact Power Sources (non-electrochemical)***: develop enabling technologies for revolutionary, non-electrochemical soldier power sources, with 10 times greater energy density than current batteries and capable of meeting the power and energy requirements of the Soldier.
- ***Fuel Cells and Fuel Reformation***: develop enabling technologies for Soldier portable fuel cell systems, including fuel processing for hydrogen generation. Provide enabling technologies for logistics fuel reformation and fuel cells for vehicle propulsion and auxiliary power.
- ***Hybrid Electric Propulsion and Power***: develop enabling technologies supporting efficient, compact, lightweight energy conversion and electric power conversion and conditioning for Future Combat System (FCS) and robotic platforms.

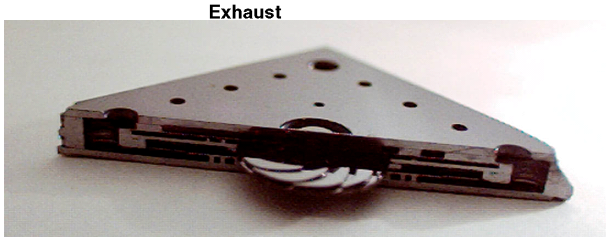
Power & Energy Research Highlights

Technical Area 1: *Compact, Portable Power Sources*

Micro Electro Mechanical Systems (MEMS) Gas Turbine Engine and Generator

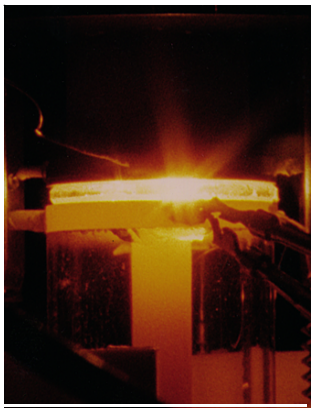
This task demonstrates the world's first microfabricated gas turbine engine that could provide a reduction in power system weight over current batteries of 2-4X in the near term and 10X in the long term, and an overall efficiency of 5-15% with liquid hydrocarbon fuel.





Microturbocharger.

This year's work focused on demonstration of a high-speed turbocharger. The turbocharger is similar in design to the engine, except it does not contain an electric generator and the compressor exit flow is exhausted out of the device and a separate pressurized air stream is provided to the turbine inlet. The turbocharger is less than 25 mm on a side and less than 4 mm thick, with an 8 mm-diameter rotor. It was spun to 480,000 rpm, equal to a tip speed of 200 meters/ second (450 miles/hour). Success of the turbocharger was spurred by the considerable progress made in developing micro gas-bearing technology for supporting the rotor.



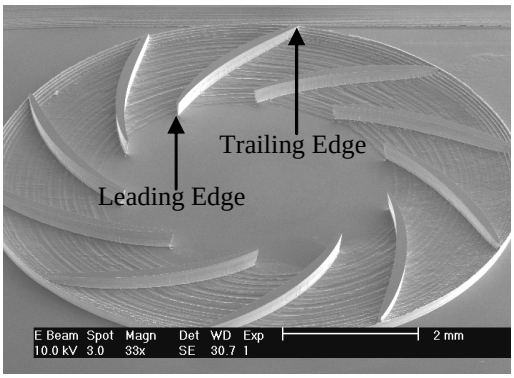
Gas-phase combustion.

Catalytic combustor.

This year also saw progress in the microcombustor for the gas-turbine engine. Gas-phase combustion is difficult at small scale because the time to traverse the combustion chamber can be less than that required to complete the combustion chemical reaction. Nevertheless, we have demonstrated gas-phase combustion in a chamber similar in size and geometry to that in the gas-turbine engine. Progress was made investigating micro-catalytic combustion as an alternative to standard gas-phase combustion. The photograph shows a piece of catalyst coated foam being inserted into a combustion chamber etched into a silicon wafer. Tests have shown that catalytic combustion is feasible in smaller volumes than gas-phase combustion. However, the maximum achievable temperature in a catalytic combustor is less than that in a gas-phase combustor, as it is constrained by the temperature limits of the catalyst and foam material. Future work will look at a hybrid catalytic/gas-phase combustor.

Variable Height Precision Deep Reactive Ion Etching (DRIE) Technology

A gray-scale microfabrication technology is being developed to enable production of complex three-dimensional (3-D) geometries in silicon not achievable using conventional fabrication methods. This fabrication process will substantially expand the design space for the MEMS gas turbine engine, improving performance. The technology utilizes gray-scale lithography for 3-D pattern definition in a masking layer and DRIE for precisely transferring the pattern into silicon.

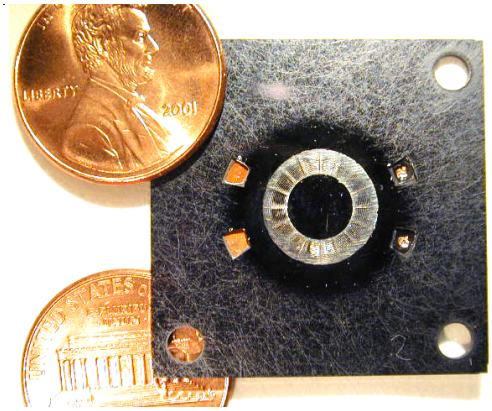


Variable height micro-compressor in silicon showing the leading edge etched 350mm and the trailing edge etched 140mm.

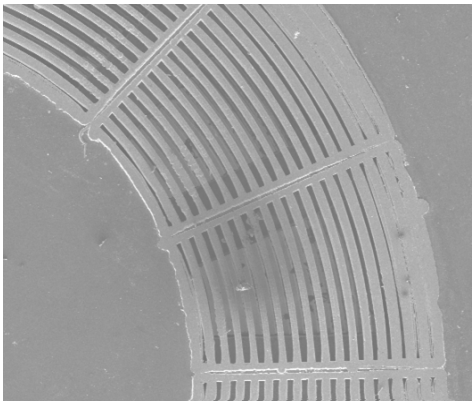
In the past year we first demonstrated a 3-D micro-compressor, shown at right. Measurements showed that our initial design exhibited improper profile characteristics. We developed a process calibration method to improve the profile integrity, meeting the profile specifications for the MEMS gas turbine engine. In addition to the improved profile, the DRIE transfer process has been fully characterized for precise height definition in the silicon. Recently, we designed a process flow to investigate integration of our MEMS-based gray-scale technology into the existing process steps for the compressor level.

MEMS Magnetic Generator Technology and Structural Design for High Speeds

Development and implementation of fabrication technology for low- and high-temperature MEMS-based magnetic generators, and the electromechanical design of such devices is being pursued because of their lower losses, favorable voltage and current levels relative to electrostatic generators. This year's efforts focused on exploring materials and fabrication processes that would allow the transition from a low-temperature epoxy based induction machine to a high-temperature silicon one. High performance materials and new fabrication methods were developed and characterized, culminating in the design, fabrication, and testing of a micromachined laminated silicon induction machine. Tests proved successful electromechanical power conversion, and a comprehensive assessment of machine performance is underway. An in-depth structural design analysis of the magnetic generator is being conducted in parallel. We observed distinctive differences in mechanical behavior of the electrodeposited nickel-iron and copper films and the corresponding bulk alloys at room and elevated temperatures. We used the experimentally measured properties as inputs to an elastic-plastic deformation finite element analysis (FEA) model of the magnetic generator with the rotor subject to



Optical image of wafer-bonded, vertically-laminated, silicon-based induction machine.



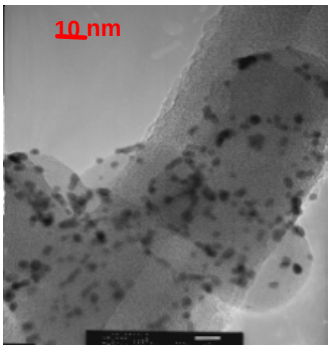
Scanning Electron Microscope (SEM) of a laminated stator.

thermal and mechanical loads, to examine the silicon rotor's ability to hold a ring of nickel-iron magnetic material at high rotational speed. The simulations showed the rotor to be subject to significant radial growth and high levels of stress, caused by thermal mismatch between the silicon structure and the embedded nickel-iron ring and by the centrifugal force due to rotation. Analysis indicates that the growth and stress can be reduced to acceptable levels by minimizing the nickel-iron used and by placing the nickel-iron as close to the center of the rotor as possible.

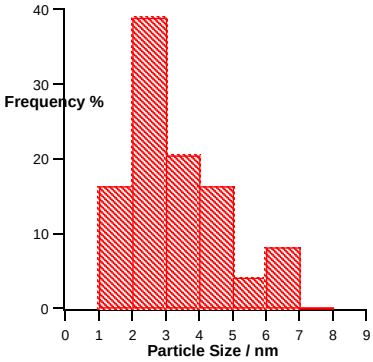
Technical Area 2: Fuel Cells & Fuel Reformation

Proton Exchange Membrane (PEM) Fuel Cells

Good progress has been made relative to research milestones. Electro-catalyst synthesis, test methodologies and fixturing have been established and several screening runs have been done with good agreement between screening, array, and single cell testing. Direct Methanol Fuel Cell (DMFC) anode electrocatalysts were synthesized with 2-3 nanometer particle size and demonstrated improved performance with 2-3 times the surface area, relative to commercially available catalysts.



Catalyst microscopic image.

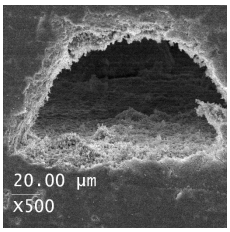


Catalyst particle size distribution.

We evaluated alternative DMFC membranes in comparison to Nafion. 1 & 2 watt DMFC prototypes were demonstrated and 1000-hour operation was demonstrated for a 1 watt system.

We developed processes to deposit catalysts directly on quartz tubes and ceramic structures, a requisite for the development of effective reformed hydrogen fuel cells. Initial testing showed comparable performance between packed-bed and wall-coated catalysts.

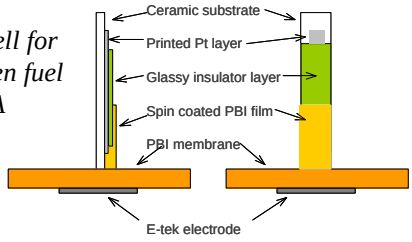
2W DMFC prototype.



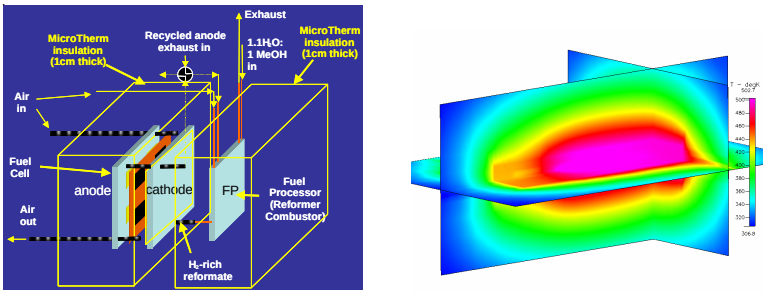
Wall-coated methanol reforming catalyst.

For high temperature Membrane Electrode Assembly (MEA) development, accurate and reproducible values for the diffusivity and solubility of oxygen are now being obtained with the Microband test fixture. Oxygen reduction kinetics on Platinum in the electrolyte were shown to be independent of relative humidity.

Microband test cell for reformed hydrogen fuel cell (RHFC) MEA characterization.



We integrated a Generation 2.5 fuel processor with a fuel cell and generated 1 watt of electrical power. Continued refinement of the 5-watt fuel processor has produced 18 amps of hydrogen (H2). Fluid-dynamics modeling of the processor gave good results for temperature and methanol concentration.



Integrated RHFC system; fluid dynamics modeling of Generation 1 fuel processor.

Solid Oxide Fuel Cells (SOFC) and Logistic Fuel Reformation

This task area focuses on fundamental research important for the development of small SOFC systems that operate directly on logistic fuels such as JP8. In the 4th quarter of FY2003, Delphi Corporation assumed the role of Industrial Lead for this area. Delphi is a major automotive component and system supplier with a significant in-house SOFC program, and an interest in small, fast start-up SOFC systems for transportation and military applications, such as vehicle Auxiliary Power Units (APUs), in the 1–10 kilowatt size range. The focus areas of research are:

Desulfurization

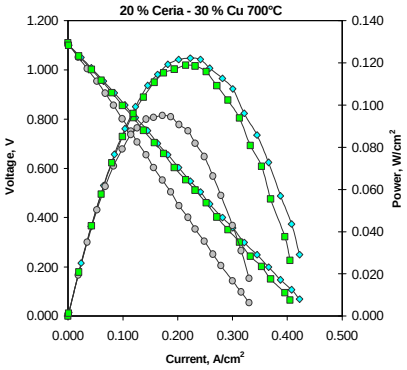
A key requirement for military applications is the need to use heavy, high sulfur, wide specification fuels such as JP8. So a sulfur removal strategy and avoidance of carbon formation in the reformer and stack are important. Our primary approach to sulfur is to develop regenerable high temperature sorbents—using Ceria as the active material. Recent results included the addition of lanthana (to reduce size) and copper (to increase capacity).

Fuel Reformation

Fuel reformation is the conversion of hydrocarbon fuel to a hydrogen rich gaseous fuel for use in the fuel cell. It can take several approaches:

- Direct oxidation or internal reforming on the stack anode.
- Exothermic, Catalytic Partial Oxidation.
- Autothermal or Endothermic and Partial Pre-reforming by several approaches.

Results this year included the deployment of automated reformer test stands, modeling of carbon formation, and testing of paraffin– aromatic blends.



Performance data obtained direct oxidation stack.

SOFC Stack

The SOFC stack is the electrochemical system that generates electricity from hydrogen and air. Stack technology is also taking parallel paths:

- Low temperature stack technologies using Copper/ Ceria anodes
- Alternative cathode and electrolyte materials to improve low temperature performance

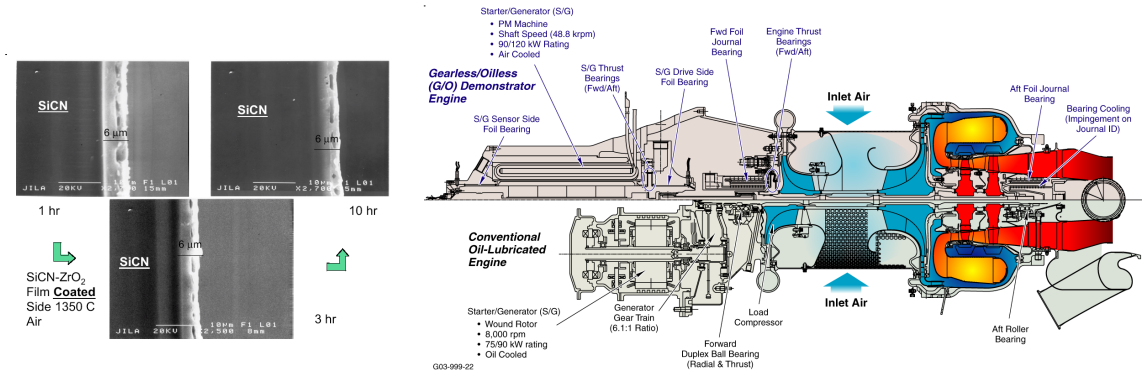
Our primary focus is on Yttria-stabilized Zirconia electrolyte materials, which can be regarded as a mainstream approach. Results included progress on direct oxidation of butane and integration of high performance cathode materials into an intermediate temperature, all-ceramic stack.

Technical Area 3: Hybrid Electric Propulsion and Power

Research in hybrid electric propulsion and power grew from a need to support the Army's vision for its Future Force, emphasizing rapid deployment of more lethal and survivable systems enable FCS with smaller logistical footprints than in the Current Force. All elements of the Army Vision (deployability, agility, versatility, lethality, survivability, responsiveness, and sustainability) will be served by developing hybrid electric systems to provide power and mobility for platforms that are enabling for FCS. How well that system generates, converts, distributes, controls, and uses power will have a significant impact on the overall success of FCS. Our work will assist in the development of the component and device technology for the subsystems and systems that will make hybrid electric systems practical and efficient on future battlefields. In addition, power and energy systems that may interact with or depend upon hybrid electric vehicles are being investigated. Examples of new efforts that will be reported next year are power systems to sustain soldier operation in the field by exploiting solar power, and an inter-CTA investigation into power and energy requirements for robots. Work last year in the three areas described below led to significant advances in understanding candidate hybrid electric subsystems. All work was connected by a parallel systems analysis effort to ensure that the work can be transitioned in the future and provide guidance to identify important issues.

High Speed Ceramic Turbogenerator

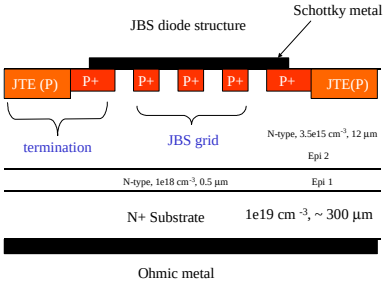
We completed a conceptual layout for a high-speed, gas-turbine-based turbogenerator in the 500-kilowatt class. A promising ceramic blade coating approach to enable high temperature turbine operation was demonstrated. An assessment of electrical machinery for the hybrid electrical drive system has been completed. High-temperature bearing hardware has been prepared for testing.



Micrograph of Zirconium Oxide layer on Silicon Nitride and foil bearing impact on APU design.

Silicon Carbide (SiC) Devices

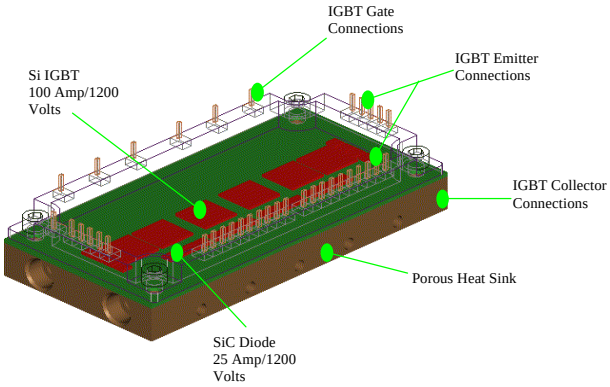
Work focused on improving fabrication techniques for SiC devices, developing test converter systems for utilization of SiC devices for matrix converters, direct current (DC-DC) converters, motor-drive converters and advanced motor designs; and developing validated models for performing designs with SiC devices. Achievements include advances in device design and fabrication techniques as well as electrical evaluation of newly fabricated devices.



1200V SiC diode structure.

Inverter & Converter Studies

Programs have consisted of component and circuit level studies. Component level design and thermal analysis have brought about the integration of SiC devices with existing silicon switch technology. We fabricated high power switch modules that can be used in many inverter and converter circuit topologies, and developed and demonstrated a new matrix converter design.



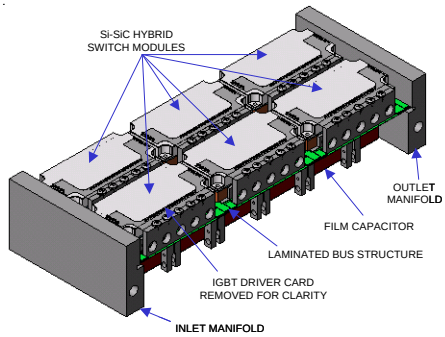
Hybrid 600 amp/1200 volt switch module.

Machine Drives & System Integration

The objective of the system design and modeling tasks was to determine the most promising insertions of these technologies for future Army applications, such as FCS and Land Warrior. During the course of the year, system performance models for a notional 16-ton vehicle were studied to investigate prime power and power distribution alternatives. We demonstrated a switched-reluctance motor controller for reduced torque ripple on a test bed and developed simulation models for the performance of brushless DC motors.

Power & Energy Technology Transitions

A technology transition of significant note is the development of a high power Silicon-SiC hybrid inverter/ rectifier. The use of SiC electronic devices in high power inverter, rectifier and converter designs promises to provide more efficient and compact devices with higher power density than previously attainable. In the Hybrid Electric Propulsion and Power Technical Area, the technology development is continuous. Development progresses from research on the fundamental device physics through the device manufacturer, to device implementation and packaging, to circuit and component design to implementation in a hybrid-vehicle architecture.



3-Phase motor drive hybrid switch inverter.

The latest SiC diodes manufactured by Cree are being used in a hybrid Silicon-SiC switch module designed by United Defense. This past year has seen technology transition occur. In the coming year, these hybrid switch modules will form the key elements to an engineering model inverter. Demonstration and testing of the engineering model inverter will be performed in the Combat Hybrid Power Systems (CHPS) System Integration Laboratory (SIL) in a working tractive vehicle simulator.

Intentionally left blank

A Message from the Robotics Leads

Mr. Charles Shoemaker (ARL)

Collaborative Alliance Manager

Robotics technology offers the Army new options in an era of rapidly evolving operational and technological challenges. The Science and Technology (S&T) investment made by ARL in robotics will also yield capabilities critical for the Future Force. An acceleration of the process of developing and implementing intelligent, ground-based, semi-autonomous vehicles is required to field the full range of these new capabilities. In particular, recent advances in commercial technologies demand a new approach to orienting robotics research work to better address dynamic Army needs and to facilitate getting the earliest possible feedback from Soldiers and applying their feedback into the research and development process.

Mr. Kevin Bonner (General Dynamics Robotic Systems)

Consortium Program Manager

The Robotics Alliance is a unique member of the ARL CTA family. The Robotics CTA (RCTA) conducts applied research, funded with 6.2 Research, Development, Test and Evaluation Program (RDT&E) funds, critical to enabling development of the Army's Future Force. The Alliance provides advanced ground robotics technology to each of the armed services, through the Office of the Secretary of Defense Joint Robotics Program. As an applied research program, the RCTA is focused on rapid technology development, working with soldiers to focus research into areas that will have both immediate and long term payoffs, gaining immediate feedback on new concepts, hardware and software. The Alliance's advanced technology products are linked to a coherent transition strategy that makes use of experimental and in-the-inventory mobility platforms to enable early user hands-on experience and assessment of progress in realistic environments.

Robotics Research Focus

In order to advance capabilities for the Future Force, RCTA research focuses on four technical areas:

- ***Advanced Perception for Autonomous Mobility***: We conduct research aimed at developing robot perception, navigation, and cooperation technologies to enable unmanned systems to join the force structure as effective members. Our focus is placed on the perception of salient features in the environment to enable the vehicle to execute tactically significant behaviors.
- ***Intelligent Control Architectures and Tactical Behaviors***: This area focuses on developing and enhancing a network-centric architecture that supports the planning and control of robotic resources [internetted, unattended ground sensors (IUGS), unmanned ground vehicles (UGVs), unmanned aerial vehicles (UAVs), etc.] in battlefield environments. This includes the development of specific behaviors and skills for autonomous implementation by unmanned systems necessary for successful operation in tactical environments.

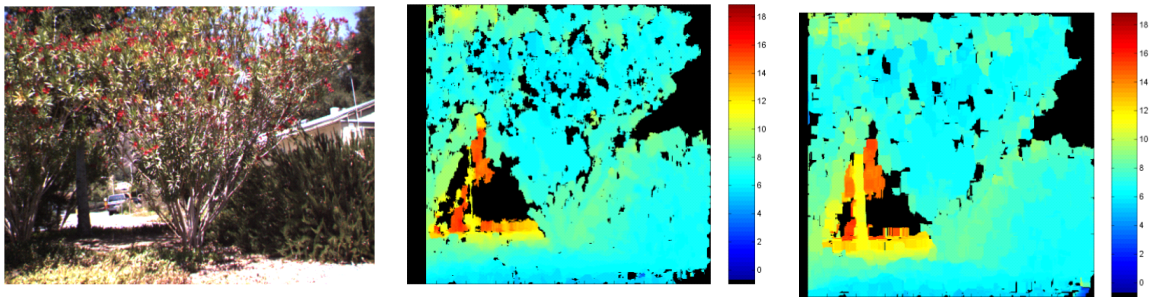
- ***Human-Machine Interface***: The main research objective of this area is to develop the underlying technologies that will reduce operator workload and provide an optimal distribution of control between Soldiers and unmanned systems. Context-sensitive multimodal interface technologies are being developed to enable operators to assess situations rapidly, respond in an effective manner, and control multiple unmanned assets.
- ***Modeling, Simulation, and Experimentation***: Modeling and simulation are used iteratively with experimentation to identify high-payoff technologies and to evaluate the effectiveness of new components, providing the driving force for directing the RCTA research.

Robotics Research Highlights

Technical Area 1: Advanced Perception for Autonomous Mobility

Sensing

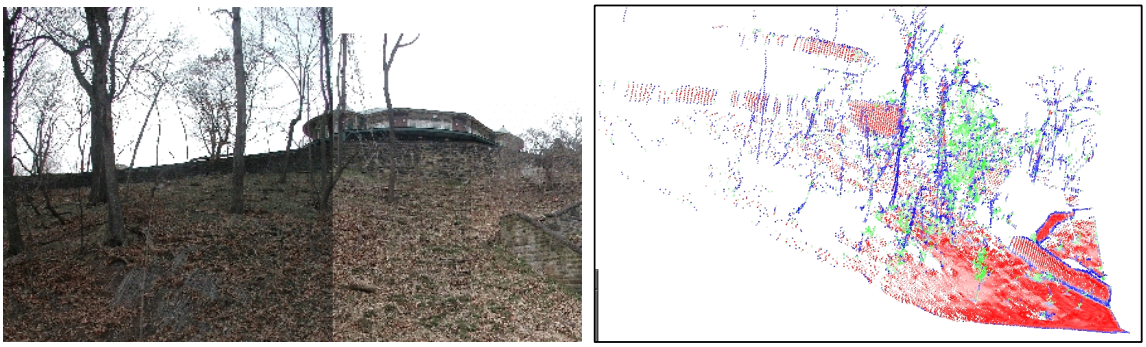
We developed new capabilities for sensing, using both passive (stereo) and active laser radar (LADAR) modalities. For stereo, we developed new techniques that are tuned to complex environments such as forests and grassy environments. The new techniques integrate visual information such as motion cues (how the images change over time) and the outlines of the objects in the scene with the standard binocular stereo approach. They lead to finer resolution and better separation of the objects from their backgrounds. For LADAR, we upgraded the CTA LADAR for improved range and resolution. We designed the new generation based on a 1550 nm laser, to be fully completed in FY04. This new generation of the LADAR will lead to a considerable decrease in detectability and an increase in speed, range, and accuracy.



Example of passive sensing from binocular stereo. Left: input scene; Center: depth map from conventional stereo; Right: depth map from CTA stereo.

Terrain Classification from LADAR

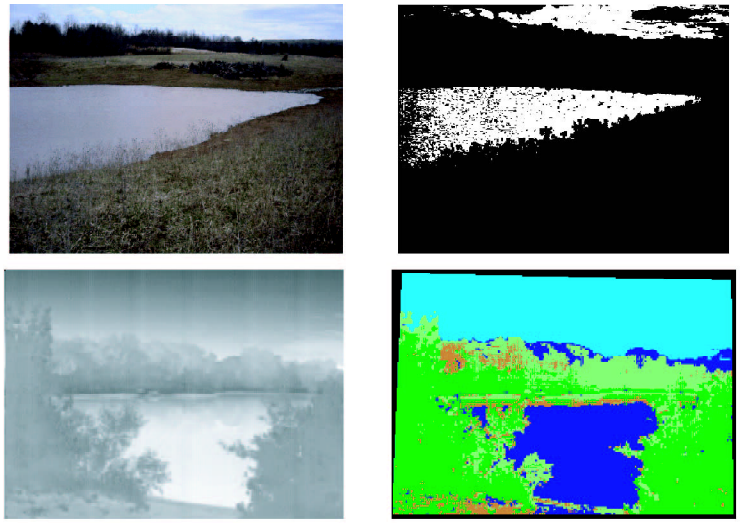
We developed new techniques for understanding the terrain in front of the vehicle from LADAR data. These techniques segment the cloud of three-dimensional points measured by the LADAR sensor into classes such as solid surfaces (e.g., the ground surface or the visible surfaces of large obstacles), vegetation, and thin obstacles (e.g., wires or poles). Current experiments in the field show that these techniques are effective in separating ground terrain from vegetation and in detecting small obstacles. In addition, we developed registration techniques that take sensor data acquired while the vehicle is moving and register it into a common reference frame. This capability will be critical in future UGV systems to compensate for errors in navigation data.



Example output from LADAR processing. Left: Input scene; Right: Classification output of 3-D points (red: surfaces, green: vegetation, blue: elongated structures).

Terrain Classification from Multiple Sensor Modalities

We developed techniques for classifying terrain types from multiple sensors (cameras, infrared cameras, LADAR, etc.). In fiscal year (FY)03, we placed significant emphasis on types of terrain that are not currently addressed in UGV systems and that are significant mobility hazards. In particular, we developed techniques for water detection from standard sensors currently found on UGVs and from new sensors, such as polarimetric cameras. Robust detection is achieved by registering and fusing multiple sensor modalities. Since the strategies used for fusing sensors are difficult to tune manually, we developed statistical techniques that learn how to combine sensor output from training data. This capability is an important step toward automatic adaptation of UGVs to new environments and missions.



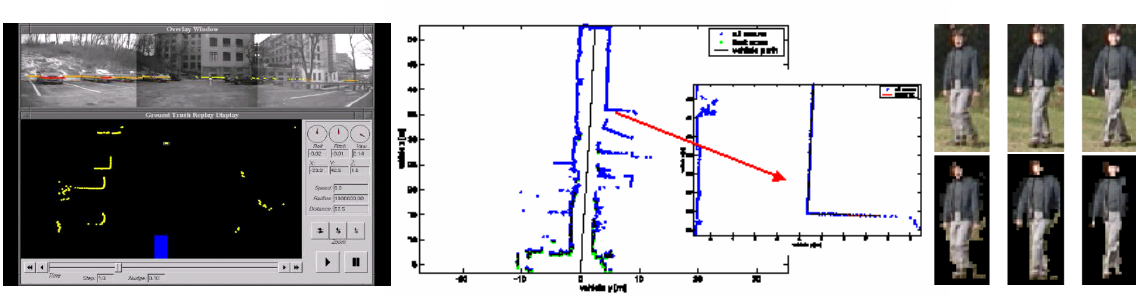
Examples of terrain classification from color imagery (top row) and from dual-band infra red (bottom row).

Mid-Range Scene Reconstruction

Determining the range and 3-D structure of distant objects is a difficult problem because existing active (e.g., LADAR) and passive (e.g., stereo) ranging techniques do not function effectively beyond a distance of roughly 50 meters. We developed techniques to estimate the range of more distant structures by using extended baseline triangulation applied to video images captured from a moving vehicle. A key element of this "structure from motion" process is the very accurate determination of vehicle position and orientation, from which the locations of objects in the scene can be determined by triangulation. The accurate position information provided by the "visual odometry" process is also of direct use in vehicle navigation, especially when operating without Global Positioning System (GPS).

Sensing for Mobility in Dynamic and Cluttered Environments

The ability to operate UGVs in urban environments, which include moving objects (other vehicles and people) and difficult to navigate cluttered spaces, will be critical in future UGV missions. To address this need, we developed a collection of perception techniques that includes the detection and tracking of people and vehicles while the UGV is moving; the automatic recovery of the vehicle position (critical without GPS) and depiction of an accurate map of the environment from sensor data; sensing at close-range for control of the UGV in cluttered spaces; and tracking of targets using acoustic sensors. While detection, tracking, and mapping are well-understood problems in situations in which the vehicle is static, the FY03 work solved the open research problem of performing the same tasks while the vehicle is on the move.



Perception capabilities for navigation in dynamic, cluttered environment: Localization and mapping (left); detection and tracking of moving objects (right).

Technical Area 2: Intelligent Control Architectures (ICA)

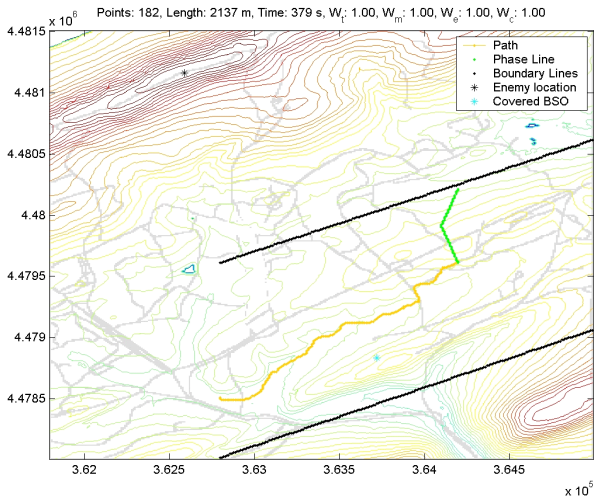
Autonomous Command and Control

In FY03, we extended the Four-Dimension Real-time Control System (4D/RCS) architectural framework to provide an architecture that fuses perception, planning, control and the Soldier. We detailed behaviors that were documented in terms of tactical skills, individual tasks and collective tasks for a Zone Recon mission as well as "move," "look," "shoot," and "communicate" subsystem level tasks. We defined and documented the canonical architecture node's external interfaces, its internal interfaces and data models for world state and physical resource state for levels above the subsystem (e.g.,

above autonomous navigation). We also formalized and implemented our Operational Command Language (OCL), understandable by both man and machine, allowing a Soldier to first form, and then task, units of unmanned assets using familiar directives and named areas/objects within the battle space. Our canonical architectural node, Autonomous Command and Control (ACC), has been designed to address the capabilities listed above and provides a framework for integrating component functionality developed under the other ICA project plans. The ACC provides functionality attributed to various reference architecture components such as the 4D/RCS Vehicle, Section and/or Platoon layers or the Joint Architecture for Unmanned Systems (JAUS) Commander(s) components.

Geometric Path Planning

To conduct tactical behaviors, unmanned ground vehicles must select tactical positions, and plan and execute routes to achieve these positions. Much of the automated reasoning is geometric in nature, including computing mobility, intervisibility, sensor coverage, communications, stealth, risk, formations, perimeter maintenance, and guarding. The vehicles must be able to re-plan in real time in response to changing conditions, tasks, and new information.



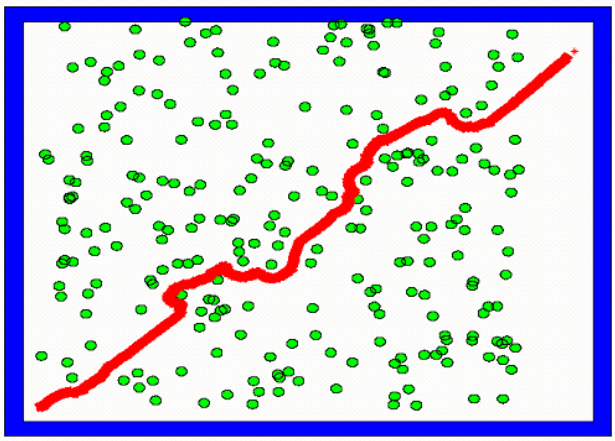
Geometric Path Planning assists soldiers in laying out routes for both manned and unmanned vehicles.

In FY03, we developed, integrated, and tested the Geometric Path Planner (GPP), designed to provide such a capability. The GPP operates on terrain elevation and feature data to generate routes that optimize and satisfy relevant tactical metrics. At present, the GPP metrics are time, mobility, exposure, and coverage; however, any number of metrics can be employed. Time is the total time required to navigate to a goal area; mobility is the total fuel consumed; exposure is the amount of time visible to a known threat; coverage is the amount of time visible to a target battle space object. The user can select one of the metrics as a hard constraint and the others as a weighted objective function to optimize. For example, the GPP can find the route that arrives at a phase line on time while minimizing fuel consumed, exposure to a single known threat, and occlusion from a battle space object under observation with twice the importance on exposure than the other two metrics.

The GPP can run on an Operator Control Unit (OCU) to assist a soldier in laying out routes for both manned and unmanned vehicles. More importantly, the GPP can re-plan the remainder of its route in real time as new orders arrive or as new information about the terrain hazards or enemy strength/ location arrives. The figure above shows a route selected (yellow) by the GPP to the phase line (green) in an area of operations (bounded by black) with all four metrics equally weighted. The threat is shown as a black star and the object to observe as a blue star.

Vehicle Control

To support autonomous mobility in difficult environments, we developed a fuzzy behavior control system for maneuvering in tight spaces such as dense woods. The control system consists of four concurrent fuzzy behaviors: obstacle avoidance, goal seeking, and left/right edge tracking. The behavior that is most suitable to the local situation at a given time dominates the control. The figure at right shows an autonomous run through a simulated forest.



Fuzzy behavior control system supports autonomous mobility in difficult environments.

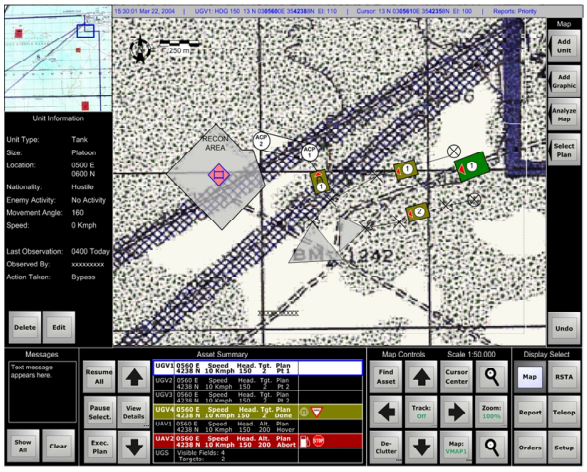
Data Fusion

To support construction and management of a consistent battle space model, we developed a MATLAB-based simulation demonstrating simultaneous localization and mapping (SLAM) among cooperating ground vehicles operating over uneven terrain. It was assumed that the vehicles carried sensors allowing them to sense landmarks, moving targets, and each other with a modest degree of accuracy. Using an implementation of decentralized data fusion (DDF) the vehicles could refine the estimates of the locations, including their own, by exchanging a minimal amount of information.

Technical Area 3: Human-Machine Interface

Integrated Soldier Machine Interface

A single screen operator control unit (OCU) for use in a HMMWV was designed and implemented for the autonomous and direct control of robotic assets. The OCU incorporates research findings from the multimodal interface and workload reduction tasks within the Human Machine Interface (HMI) technical area. The new OCU allows for on-the-move control, with larger buttons and reduced window management. The interface is designed to use existing imagery and mapping formats for easy integration. Asset control has been expanded to allow a Soldier to dynamically acquire and maintain control of multiple air and ground robotic assets. Situational awareness is improved through intelligent presentation of map information and on-screen alerting. The main displays of the interface include:



HMMWV-mounted OCU for robotic control.

- a mapping/asset planning display
- a reconnaissance, surveillance and target acquisition (RSTA) analysis and image management display
- a teleoperation display for fault and safety recovery
- a detailed reporting interface.

We are also developing an OCU for the control of robotic assets by a dismounted Soldier. The interface is designed to be used with a Personal Data Assistant (PDA)-style controller and screen for easy, one-

handed operation. This interface will have the same set of displays (mapping/planning, RSTA analysis, teleoperation and reporting) but with a reduced set of commands.

Spoken Language Interface

A functional and robust spoken language interface (SLI) was developed for both the HMMWV OCU and the dismounted Soldier OCU. The SLI is speaker and gender independent, allowing for high fidelity speech recognition without prior training of the system, even in the noisy environment of military vehicles. The SLI used a complete OCU vocabulary, where any command accessible through the touch screen interface is also available to the SLI. Finally, in both interfaces, the SLI provided a visual (text) feedback on the interpretation of the spoken phrase.

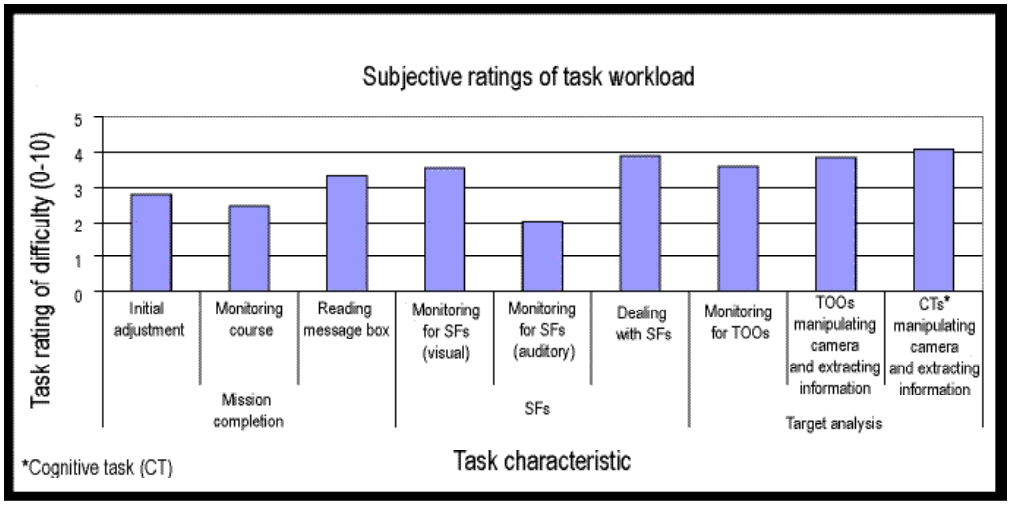
The SLI was field tested under noisy conditions for the Vetronics Technology Integration (VTI) program. Due to the large total number of commands available and to enhance the fidelity of the speech recognition, the SLI for the VTI interface used display-specific grammar. Only words and phrases that represented commands available to a given display (such as mapping/planning) would be recognized by the SLI. Field implementation of the SLI was used to address issues of signal normalization and system portability.

The SLI for the dismounted Soldier OCU (initially demonstrated at the CTA symposium in 2002) differed from the VTI SLI in that it used a display-independent grammar. This allows the operator to provide input to a display that might not be directly available through the limited inputs of the hand-held controls.

Human Performance Models of OCU Interfaces

Research in this area concentrated on the development of human performance models of the developed OCUs along with advancements in workload and trust in automation as it relates to multiple asset control. The human performance model is event driven, where a scenario event triggers an operator goal, and the operator interacts with the interface to accomplish the goal. The details of the model include an assessment of operator workload and an attention to operator resource management. Performance results for a model of a previous OCU (used in the Demo III program) compared to the HMMWV OCU indicate that design improvements and the incorporation of the SLI can significantly reduce workload and operator resource conflict.

Effects of perfect and imperfect automation on performance and operator workload were addressed in a working simulation of unmanned air vehicle (UAV) supervisory control. In these studies, imperfections in automation were better tolerated (i.e., the imperfect automation still had positive effects on overall



Subjective workload ratings for monitoring system failures (SF) and targets of opportunity (TOO).

operator performance) when the pilots had a proper sense of the degree of imperfection. Pilots were better able to judge the level of imperfection in the simulation's autopilot than the level of imperfection in the auto-alert system. While imperfection in the autopilot showed no significant performance decrement compared to perfect autopilot, imperfections in the auto-alerts at times reduced performance below the level of no automation. Workload studies using the same simulation indicated that under certain workload conditions, such as simultaneous separate cognitive and visual tasks, the pilot could enter a state of "cognitive lock" where certain tasks would be ignored despite the value or importance of that task.

Technical area 4: *Modeling, Simulation and Experimentation*

Tactical Virtual Simulation Environment for Unmanned Assets

A version 1.0 baseline has been established for the robotics software integration lab system. This system, a modified version of the One Semi-Automated Forces Testbed Baseline (OTBSAF) system coined robotSAF or rSAF, accepts Neutral Modeling Language (NML) based commands from the robotic planning software and Soldier Machine Interface (SMI), and generates robotic movement and sensor functionality within OTBSAF. This movement may be observed in 2-D on the OTBSAF plan-view-display or in 3-D on a separate personal computer running General Dynamics Land Systems (GDLS) virtual environment display software. The visual model of the eXperimental Unmanned Vehicle (XUV) is complete with articulated wheels and articulated sensor turret (RSTA). The real-time simulated entities return status messages, reports, and images back to the planning software for processing.

Dynamic Model Development for Robotic Simulation

We are developing in-house interior and exterior robotic vehicles for use in interface with control computers. Concurrently, computer and mathematical models of the robots will be developed for use in control system design and testing in a range of virtual environments. Adams models of the all-terrain robotic vehicle (ATRV)-Jr and XUV have been developed. The models include more accurate modeling of the tire and terrain characteristics, as well as more accurate physical parameters. Comparisons of the trajectories of the simulated ATRV-Jr have been compared to the actual paths taken by the ATRV-Jr using the same inputs. Once validated, scenarios that are more complex can be simulated and used to predict actual ATRV-Jr motion. A 3 degree-of-freedom mathematical dynamic model of the ATRV-Jr has also been developed. The model includes motor characteristics, various terrains, but has yet to include accurate tire slip models. The results are being compared to the Adams simulations.

A six degree-of-freedom mathematical model of the robotic vehicle has been developed to analyze the suspension behavior.

Urban Warfare Analysis for Robotic Combat Systems

This project investigates the operational modeling of robotic equipped forces using the Joint Combat Tactical Simulation (JCATS) model. An FCS-based force structure and representative threat environment are being examined. The FCS UA force structure was used as a baseline for building a robotic equipped force within JCATS. Based on the Unit of Action organization and operation (O&O) and MOUT operational vignettes, we conducted a limited number of simulation exercises to evaluate the utility of the JCATS for operational modeling of robotic platforms and evaluate its MOUT functionality. We also addressed current defense mobility and survivability (M&S) trends in MOUT modeling.

Human Performance Testing and Data Collection

Development of a testing station for thorough and synchronized data collection on Soldier performance of simulated missions using the single screen operator control unit (OCU) began during FY03. Hardware and software necessary to integrate with the OCU and provide simulated map and video displays. The test bed will consist of three systems. A OneSAF system will simulate position and tactics of friendly and enemy units. A MetaVR system will simulate the video displays of the sensors displayed in the OCU. The OCU system will display the operator user interface, allowing Soldiers to generate plans for the autonomous control of robotic assets which are sent to OneSAF and view the sensor views generated by MetaVR. Linkage of MetaVR and OneSAF was demonstrated. The OCU system is currently under development.

Robotics Technology Transitions

RCTA research in perception, intelligent control and behaviors, and man-machine interfaces provides advanced autonomous mobility capabilities required for both current and Future Force programs, as well as other ground robotics efforts for the Joint Services. The Army Semi-autonomous Robotics for Future Combat Systems (FCS) Science and Technology Objective (STO) and Robotic Follower Advanced Technology Demonstration (ATD) program are parallel efforts which provide powerful leveraging opportunities for CTA members. The Robotics CTA is a primary technology development vehicle for both programs.

Autonomous Navigation System (ANS)

RCTA provides major input to FCS' new Autonomous Navigation System development program in the areas of:

- working, field tested Laser Scanner Hardware that matches ANS emission wavelength and multi-pulse read out requirements, with 16 element detector array vice ANS' 32 element objective;
- laser processing algorithms for obstacle detection and classification;
- engineering visualization tools for laser and vehicle planner development;
- and operating robotic testbed platforms (with interfaces to navigation sensors) fully capable of data collection and archiving in realistic tactical environments.

Vetronics Technology Integration (VTI)

RCTA's transition partnership with the Tank Automotive Research Development and Engineering Center (TARDEC) has enabled transfer of the full Demo III/CTA autonomous mobility system including:

- all hardware and software,
- sensor processing algorithms,
- vehicle planners, and
- CTA's 4D Real Time Control System (4D-RCS) intelligent system control architecture.

The RCTA partnership allowed us to transition back into the CTA program the road-following software from the TARDEC VTI program and also gave us access to larger mobility platforms such as the Stryker in order to validate the performance of CTA technology. The Stryker platforms are an order of magnitude heavier than the XUV testbeds which are used for CTA development.

Demo III XUV/VTI Stryker

Substantial technology developed by the RCTA has been tested in the Demo III XUV and transitioned to the VTI Stryker platform.

RCTA has been tested in the Demo III XUV and transitioned to the VTI Stryker platform.

- Lessons from the CTA program are being put to use in the Army's Objective Force Warrior program, specifically in development of the Soldier-OCU interface, core software, and in identifying and integrating robotic assets into the OFW system.
- Common Robotic Kit—Building on lessons learned from CTA work, under a task order, GDRS developed and applied a Common Robotic Kit that controls a Meerkat vehicle for use in development of Ground Standoff Mine Detection Systems for the Joint Program Office Unmanned Ground Vehicle Systems. That system has now been shipped to Iraq for testing in the field by Soldiers during Operation Iraqi Freedom.
- UGV-ROP—Extending the application of the Common Robotic Kit design, GDRS has developed an Unmanned Ground Vehicle Robotic Obscurant Platform (UGV-ROP) for the Joint Program Office Unmanned Ground Vehicle Systems.

Alliance Members

The members of each alliance are shown in the following tables.

Advanced Decision Architectures

Industry Partners:

ArtisTech
Klein Associates
Micro Analysis & Design (MA&D) (Lead)
SA Technologies-
SAIC

Academic Partners:

Carnegie Mellon University (CMU)
Massachusetts Institutes of Technology (MIT)
New Mexico State University (NMSU)
Ohio State University (OSU)
University of Central Florida (UCF) (Associate Partner)
University of Maryland (UMD) (Associate Partner)
University of West Florida (UWF)

Government Partners:

Air Force Research Laboratory (AFRL)
ARL
Armaments RDE Center (ARDEC)
Army Research Institute (ARI)
Central Intelligence Agency (CIA)
CERDEC
Corps of Engineers (COE)
Intelligence and Security Command (INSCOM)
Natick Soldier Center (NSC)
National Aeronautics and Space Administration (NASA)
National Imagery and Mapping Agency (NIMA)
National Institute of Standards and Technology (NIST)
National Reconnaissance Office (NRO)
Naval Research Laboratory (NRL)
Office of Naval Research (ONR)
Simulation and Training Technology Center (STTC)
TARDEC

Advanced Sensors

Industry Partners:

BAE SYSTEMS (Lead)
DRS Infrared Technologies
General Dynamics Robotic Systems
Northrop Grumman
Quantum Magnetics

Academic Partners:

Clark Atlanta University
Georgia Institute of Technology
Massachusetts Institute of Technology
University of Florida
University of Illinois at Chicago
University of Maryland
University of Michigan
University of Mississippi
University of New Mexico

Federal Funded Research and Development Centers:

Jet Propulsion Laboratories

Government Partners:

AFRL
ARL
ARDEC
CIA
CERDEC
NSC
NASA
NIMA
NIST
NRO
NRL
ONR
STTC
TARDEC

Communications & Networks

Industry Partners:

BAE SYSTEMS
BBN
General Dynamics
Network Associates (NAI)
Telcordia Technologies (Lead)

Academic Partners:

City College of New York
Clark Atlanta University
Georgia Institute of Technology
Johns Hopkins University
Morgan State University
Princeton University
University of Delaware
University of Maryland
University of Minnesota

Government Partners:

AFRL
ARL
ARDEC
CERDEC
NSC
NASA
NIST
NRL
ONR
STTC

Power & Energy

Industry Partners:

Delphi Automotive Systems
Honeywell (Lead)
Motorola
NuVant
Rockwell Scientific
SAIC
UDLP

Academic Partners:

Clark Atlanta University
CWRU
Georgia Tech
MIT
Penn State University
Prairie View A&M
RPI
Texas A&M
Tufts University
University of Maryland
University of Minnesota
University of New Mexico
University of Pennsylvania
University of Puerto Rico
University Texas at Austin

Government Partners:

AFRL
ARL
ARDEC
CIA
CERDEC
COE
NSC
NASA
NIST
NRL
ONR
STTC
TARDEC

Robotics

Industrial Partners:

Applied Systems Intelligence, Inc
BAE Systems
General Dynamics Robotic Systems (Lead)
Jet Propulsion Lab
Micro Analysis & Design
Sarnoff Corporation
SRI International

Academic Partners:

Carnegie Melon University
Florida A&M University
University of Maryland

Associate Partners:

PercepTek
SSC

Government Partners:

AFRL
ARL
ARDEC
CIA
CERDEC
COE
NSC
NASA
NIST
ONR
STTC
TARDEC

Intentionally left blank

CTA Points of Contact

Consortium	Collaborative Alliance Manager	Consortium Program Manager
Advanced Decision Architectures	Dr. Michael H. Strub Telephone: (703) 253-1097 e-mail: mstrub@arl.army.mil	Ms. Susan Archer Telephone: (303) 442-6947 e-mail: sarcher@maad.com
Advanced Sensors	Dr. Dan Beekman Telephone: (301) 394-0920 e-mail: dbeekman@arl.army.mil	Mr. Stephen Scalera Telephone: (603) 885-2407 e-mail: stephen.m.scalera@baesystems.com
Communications & Networks	Mr. Greg Cirincione Telephone: (301) 394-4809 e-mail: cirincione@arl.army.mil	Dr. Kenneth C. Young, Jr. Telephone: (732) 699-2221 e-mail: kcy@research.telcordia.com
Power & Energy	Mr. John Hopkins Telephone: (301) 394-3196 e-mail: jhopkins@arl.army.mil	Dr. Mukund Acharya Telephone: (602) 231-2808 e-mail: mukund.acharya@honeywell.com
Robotics	Mr. Chuck Shoemaker Telephone: (410) 278-8810 e-mail: cshoe@arl.army.mil	Mr. Kevin Bonner Telephone: (443) 394-8979 e-mail: kbonner@gdrs.com

Intentionally left blank

List of Acronyms

1CD	1st Combat Division
3-D	Three Dimensional
4D/RCS	4 dimension real-time control system
ACC	Autonomous Command and Control
ADA CTA	Advanced Decision Architectures Collaborative Technology Alliance
AFRL	Air Force Research Laboratory
AI	Artificial Intelligence
ANS	Autonomous Navigation System
APU	Auxiliary Power Unit
ARDEC	Armaments RDE Center
ARI	Army Research Institute
ARL	Army Research Laboratory
ASCTA	Advanced Sensors Collaborative Technology Alliance
ATD	Advanced Technology Demonstration
ATR	Automatic Target Recognition
ATRV	All-terrain robotic vehicle
BCBL	Battle Command Battle Lab
C2	Command and Control
C3TRACE	Extension of Control, and Communication Techniques for Reliable Assessment of Concepts
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance and Reconaissance
CAM	Collaborative Alliance Manager
CERDEC	Communications and Electronics Research and Development Center
CHPS	Combat Hybrid Power Systems
CIA	Central Intelligence
CISD	Computational and Information Sciences Directorate
CISR	Communications, Intelligence, Surveillance and Reconnaissance
CMC	Consortium Management Committee
CMU	Carnegie Mellon University
COA	Course of Action
COE	Corps of Engineers
CONOPS	Concept and Operations
CPOX	Catalytic Partial Oxidation
CSEL	Cognitive Systems Engineering Laboratory
CSLANT	Collaborative SLide ANnotation Tool
CT	Cognitive Task
CTA	Collaborative Technology Alliance
CTAC	Collaborative Technology Alliance Conference
CW	Continuous Wave
DA	Directional Antenna
dB	decibel
DC	Direct Current
DCD	Decision-Centered Design

List of Acronyms (cont'd)

DDF	Decentralized data fusion
DDNS	Dynamic Domain Name Service
DMFC	Direct Methanol Fuel Cell
DRIE	Deep Reactive Ion Etching
DSSP	Dynamic Survivable Server Pooling
DTAL	Deputy Technical Area Lead
EO	Electro Optic
ESA	Electronically Scanned Antenna
FCS	Future Combat Systems
FEA	Finite Element Analysis
FFH	Fast Frequency Hopping
FFRDC	Federally Funded Research and Development Center
FH	Frequency Hopping
FLA	Filter Lens Array
FM	Frequency Modulation
FPA	Focal Plane Array
fps	frames per second
FTP	File Transfer Protocol
FY	fiscal year
GaAs	Gallium Arsenide
GaN	Gallium Nitride
GaSb	Gallium Antimonide
GBMC2	Ground-Based Missile Defense Command and Control
GDLS	General Dynamics Land Systems
GHz	Gigahertz
GPP	Geometric Path Planner
GPS	Global Positioning System
HBCU	Historically Black College or University
HEMT	High Electron Mobility Transistor
HEMTT	Heavy Expanded Mobility Tactical Truck
HMI	Human Machine Interface
HMMWV	High Mobility Multi-purpose Wheeled Vehicle
HRED	Human Research & Engineering Directorate
ICA	Intelligent Control Architectures
IMPRINT	Improved Performance Research Integration Tool
InAs	Indium Arsenide
ID	Infantry Division
INSCOM	Intelligence and Security Command
IPPF	Independent Partition Particle Filter
IUGS	Internetted, unattended ground sensors
JAUS	Joint Architecture for Unmanned Systems
JCATS	Joint Combat Tactical Simulation
JFCOM	Joint Forces Command Center
Ka band	27-40 GHz Microwave Band
Ladar	LAser Detection and Ranging (Laser Radar)
LADAR	Laser Radar
LAIR	Laboratory for Artificial Intelligence Research
LAMD	Lightweight Airborne Minefield Detection

List of Acronyms (cont'd)

LNS	Logical Name System
LOS	Line-of-sight (communications)
LPD	Low Probability of Detection
LPI	Low Probability of Interception
LTG	Low Temperature Growth
LWIR	Long Wave IR
MA&D	Micro Analysis and Design
MAC	Medium Access Control
MANET	Mobile Ad-Hoc Network
MANPRINT	Manpower, Personnel and Training Integration
MBE	Molecular Beam Epitaxy
Mbps	Mega bits per second
MCS	Maneuver Control System
MEA	Membrane Electrode Assembly
MEMS	Micro Electro Mechanical Systems
MHEMT	metamorphic high electron mobility transistor
MIMO	Multiple-Input Multiple-Output
MIP	Mobile IP
MIT	Massachusetts Institutes of Technology
MIUGS	Micro Internetted Unattended Ground Sensor
MMIC	Monolithic Microwave Integrated Circuit
MMW	Millimeter Wave
MOS	Metal Oxide Semiconductor
MOSAIC	Multi-functional On-the-move Secure Adaptive Integrated Communications
MOUT	Military Operations in Urban Terrain
M&S	Mobility and survivability
MSM	Metal Semiconductor Metal
MWIR	Mid Wave IR
NSC	Natick Soldier Center
NASA	National Aeronautics and Space Administration
NIMA	National Imagery and Mapping Agency
NIST	National Institute of Standards and Technology
NRL	Naval Research Laboratory
NRO	National Reconnaissance Office
NML	Neutral Modeling Language
NVESD	Night Vision and Electronic Sensors Directorate
OCL	Operational Command Language
OCU	Operator Control Unit
OFDM	Orthogonal Frequency Division Multiplexing
OFW	Objective Force Warrior
OGA	Other Government Agency
OneSAF	One Semi-Automated Forces
ONR	Office of Naval Research
O&O	Organization and operation
OTBSAF	OneSAF Testbed Baseline
PDA	Personal Data Assistant
PEM	Proton Exchange Membrane

List of Acronyms (cont'd)

PHEMT	Pseudomorphic High Electron Mobility Transistor
QWIP	Quantum Well Infrared Photoconductor
RCTA	Robotics Collaborative Technology Alliance
RDT&E	Research, Development, Test & Evaluation
RF	Radio Frequency
RHFC	Reformed Hydrogen Fuel Cell
RMB	Research Management Board
ROIC	Read Out Integrated Circuit
ROP	Robotic Obscurant Program
RSTA	Reconnaissance, Surveillance, Target & Acquisition
S& T	Science & Technology
SCTP	Stream Control Transmission Protocol
SEM	Scanning Electron Microscope
SF	system failures
SiC	Silicon Carbide
SIL	System Integration Laboratory
SIP	Session Initiation Protocol
SLAM	Simultaneous localization and mapping
SLI	Spoken language interface
SLS	Stained Layer Superlattice
SOFC	Solid Oxide Fuel Cell
STIC	Simulation and Training Technology Center
STO	Science and Technology Objective
T/R	Transmit/Receive
TAL	Technical Area Lead
TCP	Transmission Control Protocol
TEALab	Tactical Environment Assurance Laboratory
TOO	targets of opportunity
TRADOC	Training and Doctrine Command
TWNA	Tactical Wireless Network Assurance
UAVs	Unmanned aerial vehicles
UGVs	Unmanned ground vehicles
USMA	U.S. Military Academy
VB	Virtual Backbone
VTI	Vetronics Technology Integration
XUV	eXperimental unmanned vehicle

U.S. Army Materiel Command

U.S. Army Research, Development & Engineering Command

U.S. Army Research Laboratory