U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT
COMMAND –
ARMY RESEARCH LABORATORY

Research To Enable Long Term Autonomy

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Long-term autonomy is the ability to operate autonomously under no/or minimal supervision for days, weeks, months or even years.
The Army’s Corporate Research Laboratory provides foundational research in support of U.S. Army Modernization, and is focused on disruptive science and technology for the long term by performing research to answer the hardest S&T questions for future Army capabilities.

https://www.arl.army.mil/
Mission: Drive cutting edge and disruptive scientific discoveries that will enable crucial future Army capabilities through high-risk, high payoff research opportunities.

**Physical Sciences Division**
Branches:
- Chemical Sciences
- Life Sciences
- Physics

**Engineering Sciences Division**
Branches:
- Electronics Branch
- Materials Sciences
- Mechanical Sciences

**Information Sciences Division**
Branches:
- Computing Sciences
- Network Sciences
- Mathematical Sciences

Websites:
- [https://www.arl.army.mil/who-we-are/arol](https://www.arl.army.mil/who-we-are/arol)
ISD Scientific Programs

Information Science Division

Mathematics Branch
- Computational Mathematics
- Modeling of Complex Systems
- Biomathematics

Computing Science Branch
- Knowledge Systems
- Information Processing & Fusion
- Computational Architectures & Visualization
- Intelligent Cyber-Physical Systems

Network Science Branch
- Information Assurance
- Social & Cognitive Networks
- Communication Networks
- Multi-agent Network Control
Future intelligent systems will need to perform a variety of tasks in complex, possibly contested, open worlds for extended periods of time.

They will encounter previously unseen:
- Environments
- Objects and Activities
- Contexts

Future systems will need to adapt to:
- Changing internal and external conditions
- New information
- New and complex problems
Multi-Domain Operations:

...Multi-domain formations conduct independent maneuver by continuing operations in a contested environment .... Brigades, divisions, and corps, specifically, require organic mission command, ISR, and sustainment capabilities to maintain offensive operations for several days despite highly contested lines of communications.

Fighting in Urban and Complex Terrains:

“....Across the warfighting functions --whether its intelligence, surveillance or reconnaissance, collections, maneuver, force protection, command and control, logistics and sustainment--all of those things are complicated and challenged by the compartmentalized terrain that’s present in the urban environment and the 3-dimensional nature of the urban environment, which can include the subterranean environment....."

https://www.army.mil/article/215731/army_wargames_shape_the_future_of_urban_warfare
ARL’S HISTORY IN INTELLIGENT SYSTEMS

CTA- Collaborative Technology Alliance

Demo III
~1998 - 2000

CTA
2002 - 2007

Robotics CTA
2009 - 2019

Micro Autonomous Systems CTA
2008 - 2017

Distributed and Collaborative Intelligent Systems and Technology
Research Areas to Support Long-Term Autonomy

• Knowledge Representation, Reasoning and Decision Making
• Learning Theory, Methodology, and Techniques
• Assured Operations
• Interaction
Issues

• Representation and storage of information and the ability to for both long and short term memory that enables quick retrieval of pertinent information

• Optimizing the use of limited on-board storage capacity, and intermittent access to external knowledge stores.

• Developing new information through abstraction, analogy, reflection and learning

Sequencing  Spatial Reasoning  Can it move?
Issues:
What to store to support diverse (sometimes simultaneous) tasks
   Context is task dependent!
Retrieval mechanisms
   Effective use of analogy to solve problems
Updating knowledge
   Effective integration of externally supplied knowledge with observations
   Effective use of reflection and abstraction to add information to the world model
Lessons from human/animal memory

Adding Knowledge to the World Model
Abstraction
   – Guide exploration and generalization
   – Facilitate trade-offs
   – Simplify computations
   – Provides a principled method for scaling learning
Reflection
   – Make inferences from observations gathered at different times and places
   – Make connections between current observations and previously stored knowledge and beliefs
Objective
Establish new capabilities on knowledge-guided visual scene understanding, by generating and reasoning over scene graphs with the help of external commonsense knowledge.

Approach
• Use graph embedding techniques to align scene graphs with related knowledge graphs derived from text sources.
• Extends methods from open set recognition and zero shot learning to discover novel categories in open environments.
• Develop techniques to improve scene understanding from sequences of video frames.

Video Understanding
Apply graph based methods to develop a meta graph that adds newly encountered objects and relationships to an initial graph based on the first frame of the video.
Theoretical foundation for on-line or continuous machine learning

• Approaches to address both the dimensionality challenges and temporal characteristics that may be evolving continuously
• Approaches to continuous learning will allow systems to adapt to changing contexts and environments while maintaining previously learned knowledge

Issues:

• “Safe” online learning
• Intrinsically Motivated learning
• Time constrained learning
• A theory of few shot learning
• Dealing with dynamic, dirty, deceptive, dinky datasets
• Multi-task learning
• Generalization

A neural network is a mathematical function that transforms an input signal (image) to a classification (label)

- Nodes act like neurons selectively transmitting information from one layer to the next
- A weight on each arrow determines the importance of information passing from one node to the next

**Off-line Learning**

Massive datasets “train” the weights to give the best performance for all the classifications.

These are the neural nets that make the news for identifying objects, patterns, and faces.

**Incremental or On-line Training**

- Small datasets with a few classes introduced over time.
- Network retrained each time new data is added.

Neural Networks have a tendency to forget previously learned information – **Catastrophic Forgetting**
Goal: Address the catastrophic forgetting problem in continuous machine learning

Approach:
- Redesign deep neural network training process to explicitly separate the learning of the model structure from the estimation of model parameters.
- Allow network to grow or adapt as new tasks are added

Xilai Li, Yingbo Zhou, Tianfu Wu, Richard Socher, Caiming Xiong

Improved performance in sequential learning tasks
ASSURED OPERATIONS

- Test, Evaluation, Verification and Validation
- Secure operations
- Robust long term operations in poorly understood, dynamic environments

Issues
- Test, Evaluation, Verification and Validation for intelligent systems is a nascent field that needs rigorous theoretical underpinnings and practical tools.

  ...one study has asserted that in order to demonstrate a driverless car is as safe as humans, at least 275 million miles must be driven, which would take possibly up to a decade under current testing protocol

  - Shares characteristics with model checking and formal methods but...

    - Requires a systems-level evaluation of interacting components

    - Looking for relatively rare event sequences

    - Datasets, simulations and field tests need to include unsafe, aggressive, and adversarial behaviors for other actors in the scene

    - Safety monitors that prevent vehicles from violating safety constraints – it’s a start but not adequate
ROBUST LONG TERM OPERATIONS IN UNKNOWN ENVIRONMENTS

Issues

– Recognizing and responding to failure
  • Some work in reinforcement learning

– Self evaluation

– Fault Tolerance/ Safety/ Adaptation
  • Recent work on adaptation robot configurations to continue the mission

– Meta Learning/Self Testing

– Real-time performance

– Working with Uncertainty
Goal: Move Deep Neural Networks to constrained processors using compression techniques that are hardware-friendly while preserving accuracy.

- Achieve reasonable inference speeds on cell phone processors
- Achieve near state of the art object recognition

**Block-pruning**

- Divide the layer weights into equal-sized blocks of m filters and n channels
  - Size of the block is chosen based on the computational characteristics of the intended hardware
- Within block, prunes a group of weights at the same location in each filter and channel.
- GPU-CPU collaborative computing scheme further improves the computational efficiency.

**State of the Art Pruning Approaches**

**Unstructured pruning**
- **Pros:** High level of compression
- **Cons:** Inefficient computations and long inference times

**Structured pruning**
- **Pros:** Efficient computation
- **Cons:** Often eliminates important weights - less accurate models.

![Graph showing FPS vs mAP on MS COCO dataset](image)
Future autonomous systems must interact physically with humans and other intelligent systems operating in the same space, remotely with spatially distant entities, and virtually in cyberspace with intelligent software agents.

*Enable humans and robots to share the same space and work together on complex tasks.*

**Issues**

- Effective human/system interaction during training
- Effective management of faulty or unexpected behavior
- Modeling human actions, intentions and beliefs

**Sample Topics**

- Learning with human advice
- Teaming in different domains
- Adversarial Interactions
- Intermittent Communication
- Modeling Humans (Theory of Mind)
Objectives

- Develop probabilistic models that allow for rich human interaction. The key idea is to treat the experts as domain experts and solicit information from them as needed.

- Develop algorithms that can reason about what they know, explain their questions in a human interpretable manner and obtain richer forms of inputs than mere labels.

Approach

- Develop neuro-symbolic learning approaches that employ rich representations to model the domain structure and effective learning algorithms to learn from data.

- The use of symbolic representations allow for a seamless interaction with the experts, both in terms of explainability and elicitation.
CONCLUSIONS

Outlined a program to support long term autonomy

Identified 4 key research areas:

– Knowledge Representation, Reasoning and Decision Making
– Learning Theory, Methodology, and Techniques
– Assured Operations
– Interaction
Opportunities
STUDENT OPPORTUNITIES

• ORAU RAP Fellowship Program
  • The U.S. Army Research Laboratory’s (ARL) Research Associateship Program (RAP) prepares science and engineering researchers for the future. Fellowship recipients are able to advance at a top research facility while contributing to the important mission of the Laboratory

• High School Apprenticeship Program (HSAP)/Undergraduate Research Apprenticeship Program (URAP)
  • Provide authentic science and engineering research experience to high school students interested in pursuing STEM, and undergraduate students pursuing science and engineering majors

• College Qualified Leaders (CQL)
  • ARL matches talented undergraduate students with scientists and engineers in a direct mentor-student relationship, that provides the student with training, firsthand research experience and exposure to DoD laboratories that is unparalleled at most colleges

• Science, Mathematics and Research for Transformation (SMART)
  • A Scholarship for Service Program that provides the opportunity for students pursuing an undergraduate or graduate degree in Science, Technology, Engineering and Mathematics (STEM) disciplines to receive a full scholarship and be gainfully employed upon degree completion

Website:
https://www.arl.army.mil/careers/students/college-and-university/
FUNDING OPPORTUNITIES

- Single Investigator Grant
- Short Term Innovative Research Grant
  - Support rapid, short-term investigations to assess the merit of innovative new concepts in basic research
- Multi University Research Initiative
  - A tri-service Department of Defense program that supports research teams whose research efforts intersect more than one traditional science and engineering discipline
- Early Career Program
  - Attract outstanding young university faculty members to pursue fundamental research in areas relevant to the Army (within 5 years of PhD)
- Presidential Early Career Awards for Scientists and Engineers
- Defense University Research Instrumentation Program
  - Enables universities to perform state-of-the-art research that boosts the United States’ technological edge

Websites:
https://www.arl.army.mil/who-we-are/aro/
WORKING WITH ARO PROGRAM MANAGERS

Consult Broad Agency Announcement

Identify a PM

Describe research idea in a white paper

Consult with PM

Submit Full Proposal grants.gov

Review Process

Funded Proposal

• ARO is interested in basic research that develops the theory and principles that underpin science and technologies
• Research needs to support Army goals
• White paper allows PM and research to refine the research ideas to align them with the goals of the program
• PMs share white papers and proposals
• Review process involves 3 academic reviewers and 1 Army scientists
• Process requires patience!
<table>
<thead>
<tr>
<th>Army Priority Research Areas</th>
<th>ARL – ARO Investments</th>
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</thead>
<tbody>
<tr>
<td><strong>1. Disruptive Energetics:</strong> Greater than 2x energetic energy</td>
<td>Proposed ARL Program POM 22 led by ARO. Current ARO Investments design new energetic molecules that harness reactions with significant advances in the control of sensitivity (premature explosion), increases in propulsive and explosive power, and the development of materials.</td>
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<td>over smaller footprints.</td>
<td></td>
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<tr>
<td><strong>2. RF Electronic Materials:</strong> Taking advantage of optical and</td>
<td>Proposed ARL Program POM 22 led by ARO. Current ARO Investments drives basic research to enable unprecedented devices that exploit optical and electronic properties of matter for sensing, information technology, optical displays, and laser components.</td>
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<td>thermal properties of diamond materials for directed energy.</td>
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<tr>
<td><strong>3. Quantum:</strong> Optimized information transfer, sensing, and</td>
<td>ARO investments drives basic research to identify and explore quantum process in beyond-classical imaging, sensing and precision measurements, materials simulation and design, exponential speed-ups in computation, and new kinds of security protocols for networking</td>
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<td>communication with unparalleled security.</td>
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<td><strong>4. Hypersonic Flight:</strong> Aerodynamics, materials, and</td>
<td>ARO investments drives basic research underlying the flow of combusting and non-combusting fluids, and the thermo-chemical physics in energetic material initiation and burning. Fundamental discoveries in support of the Propulsion Sciences for disruptive approaches to advanced mobility and maneuver.</td>
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<td>processes.</td>
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<td><strong>5. Artificial Intelligence:</strong> Increasing speed and agility in</td>
<td>ARO investments drives understanding of how human intelligence can be automated to build AI systems that are capable of being effective decision aides, efficient as components of autonomous systems and robots, allowing robots to be near-human team-mates in Human-Agent teams of the future.</td>
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<td>which we respond to emerging threats.</td>
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<td><strong>6. Autonomy:</strong> Maneuverability and off-road mobility of</td>
<td>ARO investments develop innovative approaches for processing high performance structural materials and develop innovative new materials with unprecedented combinations and formulations of mechanical properties for breakthrough increases in agility and logistical efficiency.</td>
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<td>platforms.</td>
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<td><strong>7. Synthetic Biology:</strong> Reactive and responsive skins/</td>
<td>ARO investments specifically looks at microbes, biomolecules, DNA stability and mutagenesis, gene expression, and genetic regulatory pathways. Results will protect the Soldier from disease, develop sustainable bio manufacturing processes &amp; wide range of bio-enabled, electro-optical applications.</td>
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<td>spectrally selective materials/anti-material properties.</td>
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<td><strong>8. Material by Design:</strong> Protection overmatch against future</td>
<td>ARO investments specifically looks for extraordinary materials that can be rapidly manufactured, grown, synthesized, and produced cost-effectively to enable highly mobile, information reliant, lethal, and protected Army platforms.</td>
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<td>threats.</td>
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<td><strong>9. Science of Additive Manufacturing:</strong> For next generation</td>
<td>ARO investments drives understanding of basic research to predict and control material behavior during synthesis, processing and operation, and to predict property changes over time, based on multi-scale design of materials, exquisite control and engineering of defects, and precision integration of materials</td>
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<td>munitions for increased range and lethality.</td>
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Computing Sciences Key Thrusts

Knowledge Systems
- Adversarial Reasoning (Game Theory, Decision Theory, Bounded Rationality)
- Natural Language Processing & Affective Computing
- Network Representation and reasoning.
  - Knowledge Management
  - Army Impacts: Situational Awareness, Planning, Force Protection

Intelligent Cyber-Physical Systems
- Advanced Learning Theory, Methodology, and Techniques
- Knowledge Representation, Reasoning and Decision Making
- Assured Operations
  - Interaction

Information Processing & Fusion
- Neuromorphic Learning
- Distributed Fusion
- Intelligent Active Sensing
- Semantic Information Theory

Computational Architect. & Visualization
- Modeling, Simulation and Visualization
- Resource optimization in Multi-core and Exa-scale computing
- Optimal Algorithms for Big Data

Army Impacts:
- Better C4ISR and decision making
- Battlefield real-time computing; soldier training through simulation

Event-1
Event-2
Event-3
Trajectory
Asset-1
Asset-2
Asset-3
**Network Sciences Key Thrusts**

### Information Assurance
- Resilient and Robust Information Systems
- Autonomous cyber defense with human teaming
- Highly Assured Mobile Communications

**Army Impact:** Better preparation and more effective mitigation of cyber threats, cyber situational awareness

### Social and Cognitive Networks
- Designing High Performance Teams
- Computational Social Science
- Connecting social, cognitive, and neural networks

**Social Simulator Model**

**Army Impact:** Accelerated Team Learning, Effective Human-Agent Teaming, Community Cognitive Resilience, Simulation of Social Systems

### Communication & Hybrid Networks
- Programmable and Mission Critical Networks
- Mobile Ad Hoc and Internet of Things Networks
- Interactions between Communications, Information and User Networks

**Distributed control and optimization**
- Stochastic dynamical systems of networks of interacting agents
- Collective information processing

**Army Impact:** Battlefield Internet of Things, Machine Learning for Wireless Networks, Exploitation of Quantum Networks

### Multi-agent Network Control
- Distributed control and optimization
- Stochastic dynamical systems of networks of interacting agents
- Collective information processing

**Army Impact:** Battlefield Autonomy, Swarm systems, Neuro-cognition, Distributed information processing and assurance.
# Mathematical Sciences Key Thrusts

<table>
<thead>
<tr>
<th>Modeling of Complex Systems</th>
<th>Biomathematics</th>
<th>Computational Mathematics</th>
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<tbody>
<tr>
<td>Subspace methods/ non-smooth geometries</td>
<td>Computational Biology</td>
<td>Non-local/with-memory PDE methods</td>
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<tr>
<td>Mathematics for QIS</td>
<td>Fundamental Laws of Biology</td>
<td>Efficient billion-dof systems</td>
</tr>
<tr>
<td>Homotopy spaces over Human/Human-Machine Interactions</td>
<td>Multiscale/Inverse Methods</td>
<td>Twistronic multiscale methods</td>
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**Army Impact:**
- **Efficient data analysis/modeling, PNT, secure networking; threat detection; soldier protection**
- **Human performance, neuro-cognition, accelerated learning**
- **Improved predictive wear and maintenance, precision fires, advanced energetics, advanced actuation and mobility, wearable low power electronics**