Autonomous Systems Innovation Summit

17-18 November 2008
Office of Naval Research
Final Report

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Introduction

Office of Naval Research:
The mission of the Director of Innovation is to promote, foster, and develop innovative science, technologies, processes, and policies that support the Department of the Navy. In support of that mission, the Director of Innovation seeks to fund research that eliminates the technical barriers to achieving our critical warfighting capabilities of the future. It is imperative that we understand the high value, critical challenges and push the boundaries of our technical talent as a nation to deliver transformational warfighting capabilities to the men and women of the Navy and Marine Corps.

Overview of Summit:
The Office of Naval Research (ONR) is hosting a series of Innovation Summits on multidisciplinary topics that transcend Naval Enterprises and Naval S&T Focus Areas. The Summits connect subject matter experts across the Naval Enterprise – S&T, concept developers, OPNAV/HQMC, and acquisition.

The Innovation Summits are executed in two phases. Phase one is an internal ONR/NRL workshop to identify “tough problems” for the technical community. Phase two is designed to share our vision of future capabilities with a broad audience, and then test those capabilities in a wargame-like event (government only) to inform future concept generation.

The Summits result in focused and innovative S&T investment strategies and “technology push” for concept development and requirements generation.

Sponsors:
The Director of Innovation at ONR sponsors the Innovation Summit series in partnership with the Navy Warfare Development Command (NWDC). The Director of Research at ONR cosponsored the Autonomy Summit.

Attendance:
Phase one attendance is limited to ONR and NRL employees who can speak to the current and planned investments. These representatives are drawn from all technical and scientific disciplines across the two organizations. During phase two there is a one day event that is open to industry, and academia as well as representatives from other government and DoD organizations, but is predominantly comprised of representatives from the Navy and Marine Corps that span from S&T to Acquisition.

Background

Phase One - 23 April 2008 Autonomous Behavior Workshop:
Autonomous behavior is a multidisciplinary research area contributing to a broad range of systems, operating environments, and warfighting missions. Unlike the focus areas outlined in the Naval S&T Strategic Plan, autonomous behavior is a technical discipline that transcends the scope of any individual focus area. The research being sponsored in many of the focus areas contributes to an overall improvement in our ability to deliver autonomous behavior. However, a widespread understanding of the extent and character of the research being sponsored across ONR and NRL did not exist beyond the grassroots level.

In April, 2008, the Director of Innovation sponsored an internal workshop featuring panels and attendee from a broad spectrum of disciplines within ONR and NRL. The purpose of the workshop was to bring together multidisciplinary teams to discuss and illuminate the critical technical challenges associated with autonomous behavior. Participants were asked to identify difficult technical challenges that, if we were successful in overcoming, would result in significant and widespread progress in the area of autonomous behavior.

On April 23, 2008, researchers and program officers from ONR and NRL worked collaboratively to define autonomous behavior, examine four technical areas of autonomous behavior, and produce recommended areas for investment to further our capabilities in autonomous behavior. For the purposes of the workshop, autonomous behavior was defined as a system's ability to sense, comprehend, predict, communicate, plan, make decisions, and take sequential actions to achieve its goals as determined through interaction with humans and between units that compose the autonomous system.

However, limitations to current autonomous systems are significant. Currently, many systems require multiple highly skilled operators; users cannot easily share assets, collaborate, or get data to the tactical edge; autonomy is usually tailored to specific missions, users, and environments; and cannot be adapted to the unexpected or to the broader missions. At the same time, there are multiple barriers in the operational environments, cultural barriers, and high, often unrealistic expectations regarding autonomous systems.

Autonomous behavior and the systems that incorporate it will be seen in many operating domains, used for many missions, and on multiple platforms. Key aspects of this vision include:

- A distributed system of heterogeneous unmanned systems relying on network-centric, decentralized control that is flexible in its level of autonomy, with the ability to get the right level of information to the right echelon at the right time.
- Operations as part of a hybrid force with manned systems and platforms.

- Capabilities for automated image/scene understanding, data gathering, purposeful sensing/seeking, information analysis, and distributed information management.
- Groups of systems that will autonomously cooperate to perform a mission or task.
- Automated distribution of tasks to elements within automated system based on high-level plans, goals, and commander's intent.
- Autonomous systems that will determine the best way to accomplish each task, with appropriate human guidance, thus freeing the warfighter to maintain awareness of the entire battlespace.

To explore and identify key technical barriers to this vision, four panels worked with participants in the following technical areas:

- Human/unmanned systems collaboration
- Perception, understanding and intelligent decision making
- Scalable and robust distributed collaboration
- Intelligent C3 architectures

Workshop Results

Each panel was able to identify key technical barriers that, if resolved, would provide the most significant advancements in autonomous behavior. Those technical barriers are outlined in section three - Challenges to Autonomy.

Phase Two - 17-18 November Autonomous Systems Innovation Summit

Summit Goals and Objectives:
Phase two was designed to share our vision of future capabilities with a broad audience, and then test those capabilities in a wargame-like event (government only) to inform future concept generation. The first day of the Summit was open to industry and academia as well as government and military personnel. During that day, future capabilities the technical community believed will be available to the future Naval Warfighter were presented and discussed.

The second day of the Summit was a government only session focused around three future warfighting scenarios where multidisciplinary teams were allowed to collaborate for concept generation. These scenarios were designed to increase innovative thinking regarding potential operational capabilities with future autonomous systems.

Challenges for Autonomy

During phase one of the Autonomy Summit, program officers from ONR and NRL worked collaboratively to define autonomous behavior, examine four technical areas of autonomous behavior, and to identify difficult technical challenges that, if we were successful in overcoming, would result in significant and wide spread progress in the area of autonomous behavior. The difficult technical challenges identified during phase one are as follows:

Human/Unmanned Systems Collaboration:

- More natural modes of interaction that enable the warfighter to focus on the task, not the system; accommodating the warfighter
  - Gestures, speech, multi-touch, gaze following, augmented reality, social behavior, dialog management, cognitive models, support for interruption resumptions, and error detection
- Ability to understand intent and actions of human team members, adversaries and bystanders
- Cognitively compatible behavior during interaction to minimize human cognitive load
  - Cognitive skills, common ground, suitable ontology, social behavior
  - Getting the system to use similar representations and reasoning mechanisms as the human to be more compatible
  - How can the system best represent its state?
  - Identification and correction of errors to include transparency leading to predicting and avoiding errors
  - Activity recognition, computational cognitive models; perception
- Trading off level's of autonomy dynamically
  - Mixed-initiative interaction, cognitive skills, core intelligent autonomy

Perception, Understanding and Intelligent Decision Making:

- Autonomously adjudicate between wide area exploration and dynamic region of interest (ROI) exploitation (broad area coverage with immediate "zoom" to ROI)
  - An autonomous system should be able to recognize sensing gaps, fill gaps as appropriate, recognize when such gaps are filled, and recognize the need for additional knowledge when gaps persist
  - The system is able to decide which tasks to devote it's resources to – original larger task or more complete accomplishment of an individual task – mission optimization
- Learning context (environmental), adaptive recognition, and scene understanding to semantic level for presentation to a system or person (information is extractable)
- Autonomous vehicle tasking/maneuvering based on interaction between mission level objectives and in situ information (bottom-up & top-down) to include reprogrammable/adaptive/taskable
  - Understand if the sensing task has been accomplished and how to respond or optimize appropriately
- Automated processing (intelligence) from sensor data, to information, to actionable understanding, which is presented to potentially multiple warfighters (parsing data) and the system

Scalable and Robust Distributed Collaboration:

- Scalable, self-organizing, organizational structure/hierarchy appropriate to mission tasking

  - Robust to limited communications and uncertain or partially known information
  - Appropriate relationship between individual unit intelligence, team, coalition, and global
  - Deals with intelligent adversaries. How can these systems be disrupted/defeated?
  - Design assessment of when large numbers of platforms are preferable to smaller numbers of more capable manned or unmanned systems.
- Task allocation/assignment, planning, coordination & control for heterogeneous systems
  - Tasks have spatial/temporal dependencies w/ logical constraints on vehicles & tasks
  - Structuring of the on-board autonomy to balance multiple competing and conflicting performance metrics, and individual platform vs. group objectives.
- Airspace/Waterspace management to allow operation in close proximity to other manned and unmanned systems including crowded military and civilian areas
- Rigorous mathematical methods and tools for predicting behaviors of large numbers of unmanned systems under realistic assumptions and field testing approaches to identify potential problems and prove the capabilities and robustness of the system
  - How should we define stability, robustness, performance, controllability, etc.?
  - Tools for software verifiability and certification of complex autonomous systems

Intelligent C3 Architectures:

- Integrated Architectures
  - Integration of algorithms for perception, reasoning, learning, control, interaction, etc. is required to build autonomous systems that operate in real-time. Ad-hoc integration isn't sufficient because these algorithms mutually constrain one another
  - Must address practical concerns about the representations required. Probabilistic graphical models are great for representing some things, logic is good for others, but crossing them hasn't yet achieved a great deal of success
- Reasoning
  - Common-sense reasoning: We're still in the beginnings
- Planning
  - Anytime planning, multiple goals, partially known environment, partially known objectives
  - Plan/intention recognition: Difficult knowledge-intensive problem requiring rich inferencing in real time
  - Planning with unpredictable adversaries/coalitions: Requires plan/intention recognition, social/metacognition
- Learning
  - Learning complex concepts/tasks, group behaviors, etc.
  - Life-long learning
- Knowledge

  - Acquisition from many sources. Some recent advances in handling contradictory information, but work is in its early stages
- Social Cognition and Metacognition
  - Endowing cognitive architectures with explicit "mental models" of other agents to allow for collaboration, dialogue participation, quick strategy adaptation, socially-guided acquisition of knowledge, etc.
- Intelligence for Decentralized Systems
  - When we have Teams of Agents, these problems (e.g., decentralized planning) become even harder

The Future of Autonomy - Capabilities

The panels of ONR and NRL program officers organized during phase one were asked to consider what future capabilities could be developed if we were able to overcome the "tough problems" identified in phase one. The future capabilities identified are not focused specifically on autonomous behavior, but on autonomy in general. Some of the future capabilities are very concrete (ie. a vehicle that can perform particular functions), others are more abstract (ie. autonomous vehicles capable of sensing and responding to their environment). The future capabilities identified are listed below:

Human/Unmanned Systems Collaboration:
- Management of systems/teams at a high-level
  - Ability to *shape planning and behavior* of group of unmanned vehicles
  - Warfighter does not "control" individual platforms and instead *makes requests for information or action*
  - Can treat heterogeneous group of vehicles (air, ground, surface; different types of sensors) as a unit with range of capabilities. Tasks vehicles or groups based on information or result needed within op constraints
  - Tasking is in terms that are natural/appropriate and correspond to commanding other or human assets
  - N warfighters and M platforms -- multiple warfighters at multiple echelons can make requests of teams
- Advanced interfaces
  - More natural modes of interaction that enable the warfighter to focus on the task, not the system
  - Warfighters can use multiple modes of interaction including natural language, gestures (maps, etc), virtual or immersive environments
  - Cognitively compatible behavior during interaction to minimize human cognitive load. System responds in natural way
  - Ability to understand intent and actions of human team members, adversaries and bystanders
  - Alerting and recovery from interruption will allow faster and more accurate situation awareness
  - Error detection and correction
- Mixed-initiative

  - System allows trading off levels of autonomy dynamically and as appropriate; System can make decisions and be autonomous when required
  - Allows warfighter to attend to other tasks yet be alerted when attention is needed. System understands warfighters current level of cognitive load; can quickly bring warfighter to required level of situation awareness
  - System can explain its decisions and information on which its decisions are based. Increases warfighter trust of system
  - System can offer advice to warfighter

Perception, Understanding and Intelligent Decision Making:

- Autonomous target detection, geolocation, recognition and tracking from the distributed system of sensors across all target and environment types
- Cross-cueing and coordinated tasking across autonomous sensor platforms to enable common picture (detect, classify, identify, locate and track)
- Autonomous adjudication and tasking between wide area exploration and dynamic region of interest exploitation
- Inferring hostile intent: Mission-related scene understanding and
- Identification of cues in data that provide clues about intent, activity recognition, recognition of anomalous behaviors
- Learning context and environment and adapting sensors and processing appropriately
- Autonomous vehicle tasking that reflects both mission objectives and emerging sensed contingencies
- Automated processing and fusion from multiple sensors including intent recognition and eventual presentation of knowledge to the warfighters

Scalable and Robust Distributed Collaboration:

- Get autonomous system services to the tactical edge
  - User requests ISR services in a natural way and does not need to deal with how this will be achieved
  - Helps user find mobile, difficult to detect/ID targets in difficult terrain/environments
  - Provides tactical intelligence for unit self-protection
  - May act in way to minimize chance of enemy detection
  - Man-portable systems & systems dispensed by larger unmanned or manned vehicles
- Multi-UV Teams for Force protection in the littorals
  - Unmanned forces sent ahead while high-value manned assets kept out of harm's way
  - Detect, provoke, disrupt asymmetric threats
  - May act as decoy, absorb enemy resources, or limit enemy options (e.g., if they know they are being watched)
  - Decentralized with very fast reaction when needed
  - Operates in close proximity to manned platforms safely
  - Limited manning on-board ships to operate

  - Mix of large/small unmanned vehicles and deployable sensors for MCM/ASW/ASuW/ISR
- Large, Adaptable, and Extendable Sensor Network
  - Limited network in place in harbor that can be extended as required
  - Can remain in place for long time period and activated as needed.
  - Humans can interact at different levels (e.g., task entire network at high-level or provide specific details for complex task like hull/infrastructure search in difficult environment)
  - Mobile systems can operate around manned systems safely
  - Can provide data on threats that are difficult to detect/ID, but substantial need for human involvement.

Intelligent C3 Architectures:

- Advances in solving Hard Problems in “Intelligent C3 Architectures” do not generally by themselves lead to stand-alone capabilities. They contribute to and enable the following capabilities discussed by Panels 1-3:
  - Human-Machine Interactions
    - Hard Problems: Reasoning, plan recognition, knowledge, learning, social cognition, and cognitive architecture
  - Coordinated Operations by Teams of Autonomous Systems
    - Hard Problems: Decentralized reasoning, planning and plan recognition, knowledge management, learning, and intelligent architectures (for individual agents and teams of agents)
  - Scene Understanding
    - Hard Problems: Learning, knowledge acquisition, reasoning (about sensor data and the scene), planning (to obtain additional information), plan recognition, and architecture
- Additional Capabilities
  - Rapid Deployment of Autonomous Systems
    - An autonomous system’s ability to reason, plan, learn, and coordinate with other systems enables it to adapt to unforeseen situations. It reduces the need for time-consuming, pre-mission, detailed modeling, planning and tasking.
    - Plug-and-play new assets/payload
    - Post-deployment adaptability, with minimal warfighter intervention, is particularly important for long-duration missions, where planning becomes impossible (e.g. persistent surveillance).
  - Training
    - Simulated environments with intelligent agents for realistic warfighter training
  - Intelligent Assistant
    - Software Agents that learn what the user does through instructions and observations
    - Reduce the cognitive load, perform repetitive and tedious tasks
  - Detect, Prevent, Mitigate Cyber Attacks

- Large numbers of cyber agents observing and learning internet activities can provide warfighters real-time automated capabilities to
- Detect abnormal activities
- Prevent potential attacks (e.g. denial of service, virus propagation)
- Plan to mitigate the effects of such attacks when they occur

Autonomy in Future Warfighting Scenarios

Summit attendees were divided into six groups to participate in a "game like" event where the future capabilities were tested in future warfighting scenarios. The scenarios were designed to facilitate thinking on the use of innovative autonomous capabilities, but were not intended to provide a complete picture of our future environment.

Participants were asked to make assumptions in their breakout teams and rely on their backgrounds and experiences as well as imagination and innovative capabilities to approach the task. There were no wrong answers or preconceived and anticipated findings. Two independent teams worked on each of the three scenarios resulting in six unique perspectives.

Through this process, the Summit organizers hoped that participants would gain an understanding of the future capabilities the technical community believes will be available to the future Naval Warfighter; collaborate in multidisciplinary teams for concept generation; increase innovative thinking regarding potential operational capabilities within specific scenarios; and generate new ideas for the Science and Technology (S&T) portfolio.

Breakout teams were asked to document their work and report back to the general session with their findings. Specifically, they were asked to:

–Strategy and execution:
- •What general warfighting approach did you take to achieve the tasking for your scenario?
- •What assumptions did you make?
- •Are there assets you used that were not listed in the Blue Order or on the New Capabilities List?
- •Why were you successful?

–New capabilities:
- •Which capabilities contributed significantly to the success of the mission, and why?
- •Which capabilities were incorporated into specific platforms?

•Present your findings to the general session in 20 minutes

The three scenarios were designed to encourage the use of autonomy. The following is an overview of the three scenarios used. Fictitious names of people, places, organizations and countries were used to keep the scenarios unclassified and timeless.

Maritime Improvised Explosive Devices (MIED) in CONUS Ports:
The year is 2020, a coordinated attack on our gulf coast offshore port resulting in loss of the port. A short time later, an M-IED is detonated under a container ship in a major shipping channel, closing the channel. Nearly simultaneously, a second coordinated attack is conducted on an oil tanker outside a major west coast commercial port using remotely operated personal watercraft. The attack successfully breached the hull and spilled a large amount of oil into the water. The mission is to clear the port of M-IED and other threats and prevent the reseeding of these threats within 48 hours. Additionally, for a two-week span you must protect the port and its associated assets against further attacks.

Maintaining the Sea Lines of Communication (SLOCs) in the Strait of Hormuz:
The year is 2018, the country New Homeland has become increasingly aggressive toward its neighbors and the U.S. and has just tested a new anti-ship missile with a 200nm range. New Homeland owns three Gas and Oil Platforms (GOPLATS) at the entrance of the Strait in the Gulf of Oman. They then attack and take control of two GOPLATS owned by the United Arab Emirates (UAE) in the Persian Gulf, thereby gaining control of the Strait. The UAE requests and the U.S. agrees to reestablish the SLOCs in the Strait. The U.S. deploys a carrier strike group to the Area of Responsibility (AOR). The mission is to seize control of the GOPLATs formerly owned by the UAE, and reestablish the SLOCs in the Strait within 48 hours of arriving in the AOR. Additionally for two week you must protect and prevent future strikes against GOPLATs and shipping assets in the Strait and maintain the SLOCs in the Strait.

Weapons of Mass Destruction (WMD) in a Rogue Nation:
The year is 2020, in an area that has become known as Kushan. The government of Kushan disintegrates in a civil war and the staff at the WMD facility flees the facility and leaves it unguarded. Intelligence reports indicate that three groups depart with items of value, and communications traffic indicates an imminent use of these weapons. Three teams of fifteen special operations forces are deployed to determine if special weapons exist, locate them, and characterize them within three weeks. It is imperative that they remain undetected, and are augmented by a broad range of autonomous systems. The intelligence reports suggest that the three groups are distributed in three different areas of Kushan – one is urban, one is desert, and the other is mountainous.

Key Observations and Insights

While each of the teams were asked to evaluate the future capabilities within a single scenario, commonalities in their findings were easily found. All of the teams used the autonomous systems to reduce the need for humans to operate in environments that were contaminated, remote and difficult to reach, or were unsafe due to threats from some other group. In some cases, no humans on the ground were used at all. Some common themes include:

- Use of teams of heterogeneous autonomous systems to collaborate in dynamic ways to accomplish a mission, used by a warfighter not on the scene to inform decisions and tactics.
- Use of human – robot teams in high risk environments to detect, identify and neutralize threats in urban environments.
- Use of autonomous agents to monitor email, websites, social networking sites, cell phone, land phone and travel of known entities of interest, and provide information of interest to the warfighter to track threats, intentions, and items of interest.
- Surveillance of large, complex areas with collaborative systems of systems (air, ground, underwater, communications) approach including manned and unmanned systems.
- Automated asset allocation tools were able to assist in rapid mission planning and flexible tasking for large numbers of autonomous systems and warfighters in dynamic environments.
- Communication between human and machine is natural and intuitive, and trust between human and machine exist, even in life threatening situations.
- Autonomous adjudication and tasking between wide area exploration and dynamic region of interest exploitation.
- Systems were used in varying levels of autonomy, as required by the mission – not all levels of autonomy in each system were used and were able to be managed as appropriately by the warfighter.
- Networks of sensors were used in high risk areas prior to the events (insitu) outlined in the scenarios to provide intelligence on conditions over time, and then used for change detection that could then be automated.

Some common technical requirements to reach the full potential for the autonomous systems, and have them provide the warfighter with new capabilities include:

- Large sensor data fusion and extraction was used to support the autonomous systems and to make their information valuable to the warfighter for decisions and tactics.
- Ability to deliver information quickly and appropriately to distributed autonomous and human systems anywhere at any time is critical to the development of a trusted autonomous system/human team.
- Persistent surveillance with automated change recognition on items of interest from autonomous systems is a key component to how the teams used the systems – without that, they may not have been as valuable.
- Systems will need to be adaptive and multimodal to fill multiple missions in changing environments.
- Automated error detection and correction is essential if autonomous systems are going to be weaponized and/or trusted by teams.
- Autonomous systems will need to be able to deliver tagging technologies and the track, listen, and localize items of interest.

- Communication tools for the individual warfighter – especially distributed across the battlefield must have the necessary band width, persistent power, and have universal interaction (web, cell, text, video, data, etc…)
- Systems must be able to explain decisions to the operators.
- Ability to quickly launch, replenish and recover autonomous systems from multiple platforms and domains.

Fostering an Environment of Innovation - the Office of Naval Research and Navy Warfare Development Command Collaborative Efforts

ONR and NWDC are collaborating to ensure that future technology is incorporated into the concept generation and development process and that the S&T program is informed by the future warfighting visions that come from that process. It is expected that NWDC will leverage this collaboration to refine expectations based on warfighter challenges to give our concept development the spectrum of vision necessary and to provide doctrine writing teams with an understanding of what may be technically feasible in the future.

In order to be successful, ONR and NWDC will work together to develop a roadmap for continued interaction. That roadmap will assist the leadership of ONR and NWDC in gaining a strong understanding of the other's mission and vision. The ultimate objective is to harness the power of both organizations to foster an environment of innovation.

The Autonomous Systems Innovation Summit has been a pilot project in this new collaborative relationship. NWDC Commander RADM Wendi Carpenter and her key senior staff attended and participated in the two day event. ONR and NWDC are also collaborating on a similar event focused on the undersea environment.

Conclusions

This first Innovation Summit helped to bring the S&T and Operational communities together with the Concept Developers and allowed them to work collaboratively on a future vision for autonomous systems. The findings outlined above will help the S&T community focus their efforts in ways that will pay the best dividends for the warfighter. At the same time, it has illuminated the relationship between autonomy and other areas of S&T that must be delivered for the autonomous systems to be as effective as we envision.

Interaction between these communities will continue in an ad-hoc manner around this topic in the future. ONR will host a Progress Meeting for those in industry and academia that have research funding from ONR in the spring of 2010.

The next Innovation Summit will focus on Large Data Sensor Fusion and Extraction, and will follow the same format.