# DoD Autonomy Roadmap
# Autonomy Community of Interest

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**Autonomy COI Lead**

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# Outline

Overview of the Autonomy COI

- Setting the Stage
- COI purpose & steering group
- Autonomy Drivers

Autonomy Portfolio

- MRPI, HASIC, STAS, TEVV
- ARPI

Industry Opportunities

- Enduring gaps
- Defense Innovation Market

# Setting the Stage

## Defense Science Board July 2012 Task Force Report

**Autonomy is a capability (or set of capabilities that enables a particular action of a system to be automatic or, within specified boundaries "self-governing."**

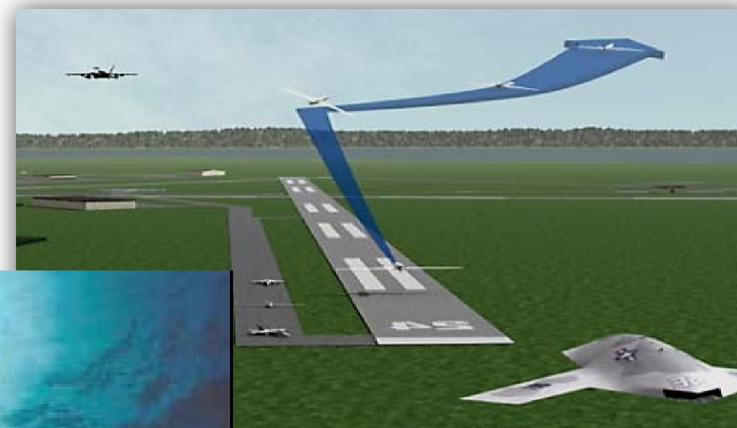
- **The DoD should embrace a three facet autonomous systems framework**
  - **Cognitive echelon – scope of control**
  - **Mission timelines – dynamic redistribution of responsibility**
  - **Human-machine trade spaces**
- **Structure autonomous systems acquisition programs to separate autonomy software from the vehicle platform**
- **Create developmental and operational test and evaluation (T&E) techniques that focus on the unique challenges of autonomy**

***Neither Warfighter nor machine is truly autonomous***

# Breadth of Autonomy

*Air, Land, Sea, Cyber, Non-Physical Systems*

Space



Air

Sea

Cyber

Land

# Autonomy Community of Interest (COI)

***Purpose:*** **Closely examine the DoD's S&T investments in the enabling of autonomous systems, to include the strategic assessment of the challenges, gaps, and opportunities to the development and advancement of autonomous systems, and identification of potential investments to advance or initiate critical enabling technology development.**

**The Autonomy COI provides a framework for DoD scientists, engineers, and acquisition personnel to:**

- **Engage in multi-agency coordination and collaboration**
- **Report on the "state-of-health"**
- **Identify emerging research opportunities**
- **Measure progress**

## Autonomy COI Steering Group:

# Technology Portfolio

## *What's driving Autonomy S&T?*

- Manpower efficiencies (reduce human footprint and personnel cost)
- Rapid response and 24/7 presence (timely, persistent, enduring)
- Harsh environments (day, night, hot, cold, bad weather, rubble, barriers)
- New mission requirements (increasing competence enables new capabilities)
- Advanced medical applications (critical response, end-to-end critical care)
- Logistical support (reduce logistics burden: hold, transport, carry, watch)

### Technology Taxonomy (Tier 1)

**Machine Perception, Reasoning and Intelligence**

**Scalable Teaming of Autonomous Systems**

**Human/Autonomous System Interaction and Collaboration**

**Test, Evaluation Validation and Verification**

# Tier 1
# Brief Descriptions

**Machine Perception, Reasoning and Intelligence (MPRI):**
Perception, reasoning, and intelligence allows for entities to have existence, intent, relationships, and understanding in the battle space relative to a mission.

**Human/Autonomous System Interaction and Collaboration (HASIC):**
The keys to maximizing the human-agent interaction are: instilling confidence and trust among the team members; understanding of each member's tasks, intentions, capabilities, and progress; and ensuring effective and timely communication. All of which must be provided within a flexible architecture for autonomy; facilitating different levels of authority, control, and collaboration.

**Scalable Teaming of Autonomous Systems (STAS):**
Collaborative teaming is a fundamental paradigm shift for future autonomous systems. Such teams are envisioned to be heterogeneous in size, mobility, power, and capability.

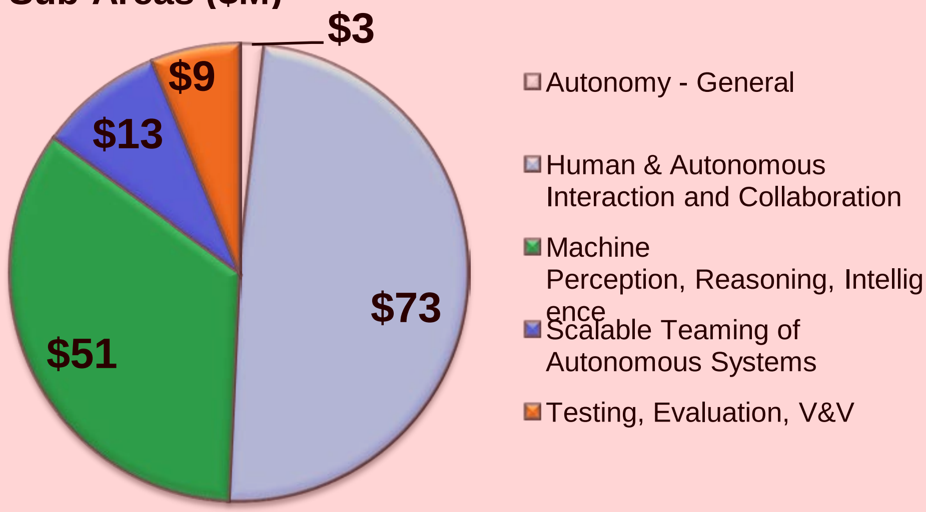
**Test, Evaluation, Validation, and Verification (TEVV):**
The creation of design based verification and validation (V&V) methods and novel developmental and operational test and evaluation (T&E) techniques that focus on the unique challenges of autonomy, including state-space explosion, unpredictable environments, emergent behavior, and human-machine communication.

# Autonomy S&T Funding Distributions

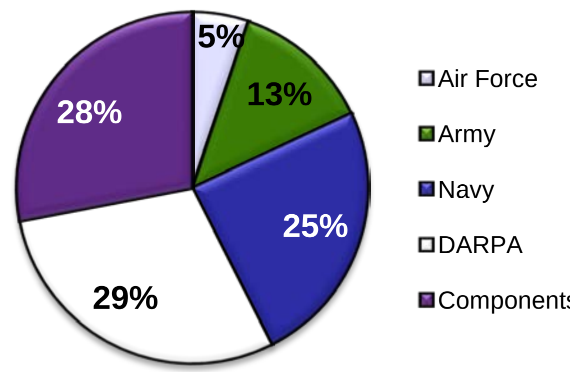
Total = $149M

**DoD PB15 FY 2015**

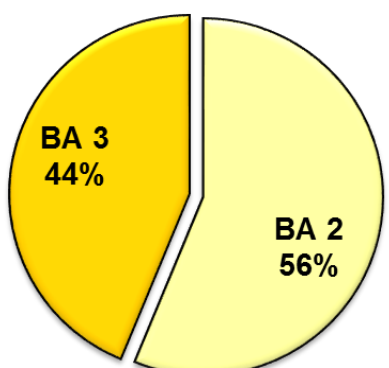
COI Sub-Areas ($M)




**By Component Investment**




**By Budget Activity**




- **Funding across DoD in Autonomy**
- **Autonomy appears across many COI's**
- **Based on FY15 Presidential budget**

**Distribution A.** Approved for public release: distribution unlimited.

# Machine Perception Reasoning & Intelligence (MPRI)

## Goals:

**Common Representations/Architectures**

- Development of a common construct of knowledge for all entities in the mission space. Knowledge may be represented in a procedural format and/or in a format that can be analyzed and decomposed independent of its content through inference.

**Learning and Reasoning**

- Development of methods for entities to evolve behaviors over time based on a complex and ever-changing knowledge base of the battle space.

**Understanding the Situation/Environment**

- Development of methods for shared understanding amongst entities of the battle space in the context of mission, background knowledge, intent, and sensor information.

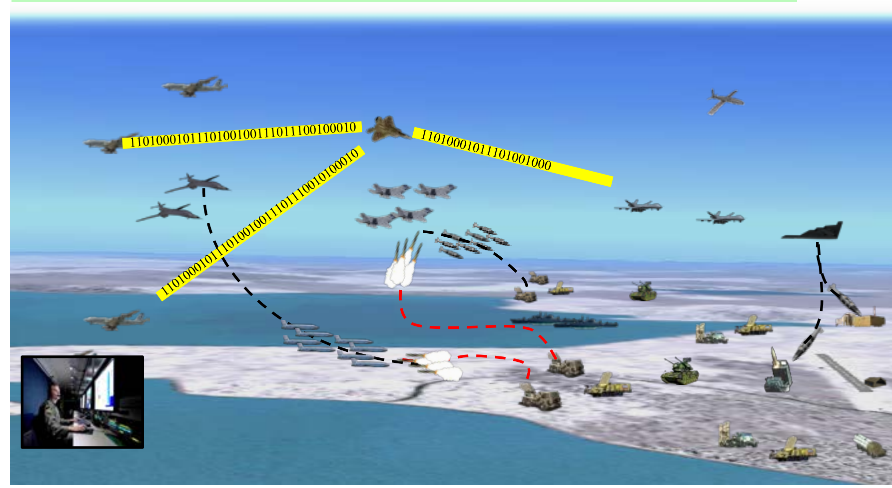
**Robust Capabilities**

- Fundamentally explore system paradigms to ensure behavioral stability in the face of increasing complexity and uncertainty. This is especially important in implementation.

## Central Technical Challenge:

**The underlying perceptual, reasoning, and learning capabilities to greatly reduce the need for human interventions, while enabling effective teaming with the warfighter**

## Highly Capable Unmanned System:



**Co-leads: Greg Hudas, TARDEC**
**Jim Overholt, AFRL**

# Machine Perception Reasoning & Intelligence (MPRI)

## Technology Trends (Evolving):

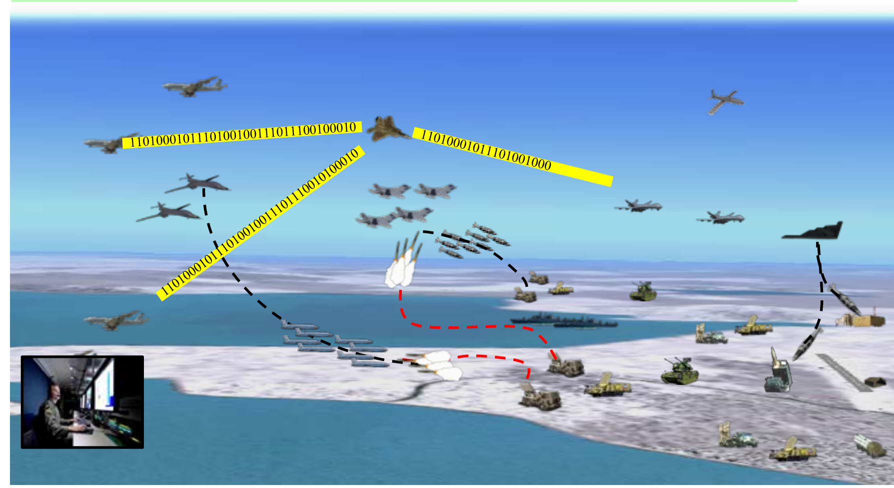
- **Near Term:**
  - Development and use of ontologies to enable behavior development
  - Utilization of supervised learning dependent upon creation of significant corpus of sample data
  - Object/behavior classification at less than “real-time”
  - Automation of low-level behaviors
  - Model-Free analytics of data bases

- **Far Term:**
  - Ontologies adjusted through common-sense knowledge via intuition.
  - Learning approaches based on self-exploration and social interactions.
  - Shared cognition
  - Behavioral stability through self-modification.
  - System self-awareness

## Central Technical Challenge:

**The underlying perceptual, reasoning, and learning capabilities to greatly reduce the need for human interventions, while enabling effective teaming with the warfighter**

## Highly Capable Unmanned System:



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# Machine Perception Reasoning & Intelligence (MPRI)

## Hard Problems:

- Learning context, adaptive recognition and scene understanding to semantic level for presentation to a system or person
- Processing of sensor data to information to actionable understanding presented to the warfighter and the system to include multiple warfighters or entire system
- Autonomous systems that appropriately use internal model-based/deliberative planning approaches and sensing/perception driven actions/control
- Representations that support perception and intelligent behavior
- Autonomously adjudicate between behaviors, e.g., wide area exploration and exploitation of area, entity, sensing modality, etc.

## Central Technical Challenge:

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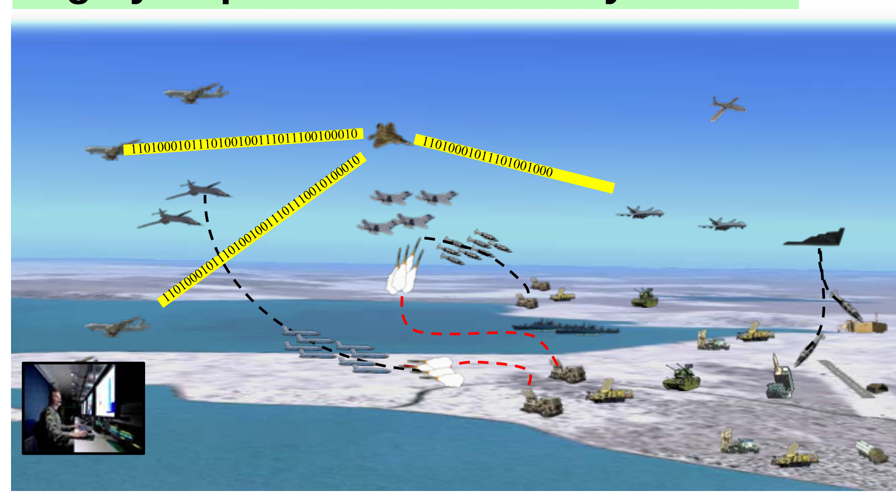
## Highly Capable Unmanned System:



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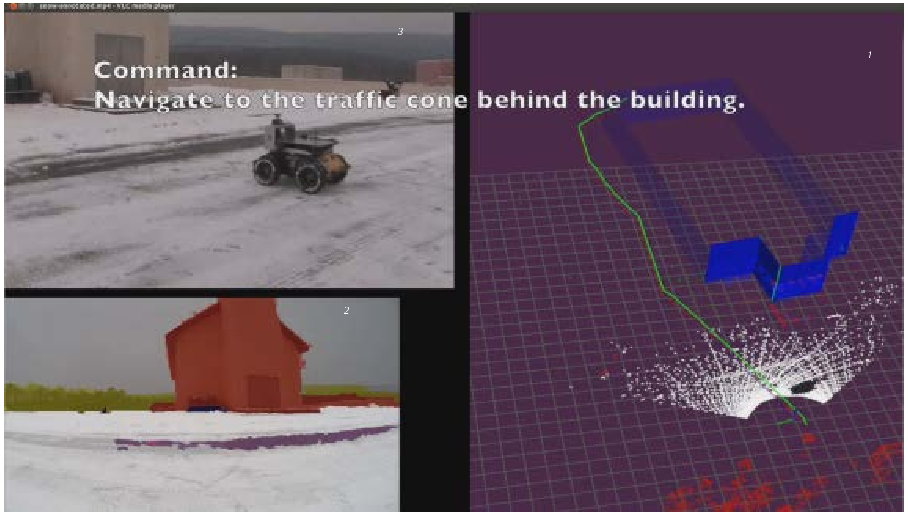
# MPRI: Robotics Collaborative Technology Alliance



Engineering display screen shot from recent experiment

**Description:** Conducts research in perception, learning and reasoning, human-robot interaction, manipulation and unique mobility to achieve greater levels of autonomous behavior and mobility for future unmanned systems; aim to unburden the soldier and enhance situational awareness

**Current Status:** Initial instantiation of a hybrid architecture has been created and integrated on a small commercial platform.

## Recent Accomplishments

- **Instantiated hybrid cognitive/metric architecture to facilitate teaming of soldiers and robots**
- **Developed behavior descriptions based upon experience with natural language constructs**
- **Created algorithms for semantic labeling of objects and behaviors, extensive use of supervised and unsupervised learning**
- **Conducted laboratory demonstration of active LADAR sensing**

## Approach:

- **Advance capabilities in five fundamental (multi-disciplinary) technologies: hybrid cognitive-metric architecture, learning, semantic perception, behavior generation, & shared (human-machine) mental model of the environment .**
- **Employ extensive modeling and simulation to prove component technology, explore integrated capabilities**
- **Conduct structured live experimentation to assess performance and validate M&S results**

# Human/Autonomous System Interaction and Collaboration (HASIC)

## Goals:

**Calibrated trust:**

- Collaboration means there must be an understanding of and confidence in behaviors and decision making across a range of conditions. Agent transparency enables the human to understand what the agent is doing and why.

**Common understanding and shared perception:**

- For humans and agents to have shared understanding, perception, and situational awareness, data and information must be in common representations and transmittable in discernible formats and timescales.

**Human-Agent Interaction:**

- The environment must allow for fluid, free-flowing, and prompt interactions. Hand-off of task execution and decision making must be graceful and flexible. The "system" (both human and machine) must be able to adjust the level of authority and decision-making based on the mission situation and relative performance.

## Central Technical Challenge:

**Shared perception, understanding & collaboration**

## Trusted Autonomous Systems:

**Co-Leads: Alan Schultz, NRL**
**Will Curtis, AFRL**

# Human/Autonomous System Interaction and Collaboration (HASIC)

## Technology Trends:

Near Term

- Improved Human-Machine Communication
  - Improved machine understanding of voice & gesture
  - Employment of abstract representations
  - Requires appropriate data sets
  - Desire for Transparency/accountability
- Mid Term
  - Improved methods for sharing of authority
    - Employs static measures of effectiveness to assess performance
- Far Term
  - Context aware interaction
    - Awareness of "commanders intent"
    - Use of indirect feedback mechanisms

## Central Technical Challenge:

**Shared perception, understanding & collaboration**

## Trusted Autonomous Systems:

Co-Leads: Alan Schultz, NRL
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# Human/Autonomous System Interaction and Collaboration (HASIC)

**Hard Problems:**

- **Natural modes of communication (bi-directional) between human and machine**
  - Maintain warfighter situational awareness
  - "Converse" in the warfighter's language
- **Cognitively compatible behavior**
  - Common ground – understanding of the environment: physical, social/behavioral
  - Transparency – ability to understand teammate actions
  - Recognition of activity; recognition of change/exceptions; recognition of deception
  - Understanding commander's intent
- **Dynamically changing level of interaction**
  - Recognition that relative levels of competency for humans and machines is dynamic – how does the system (human & machine) smoothly transition

**Central Technical Challenge:**

**Shared perception, understanding & collaboration**

**Trusted Autonomous Systems:**

**Co-Leads: Alan Schultz, NRL**
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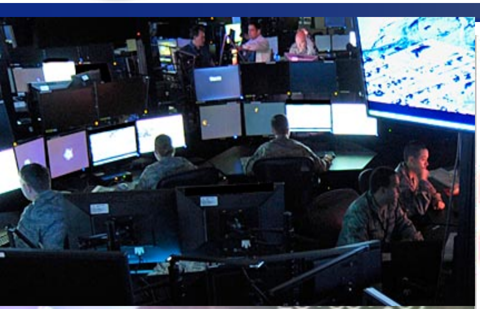
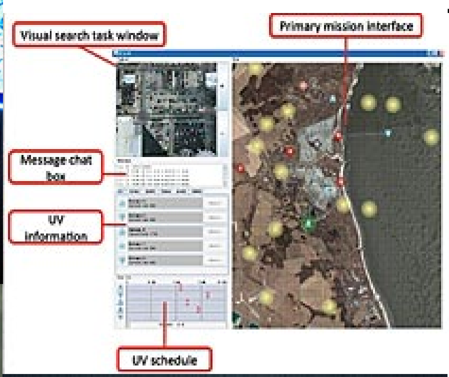
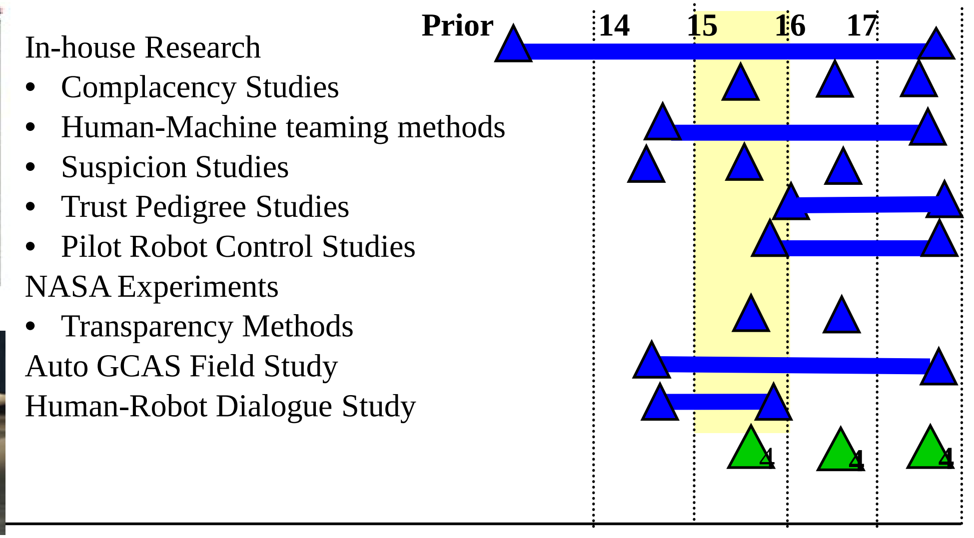
# HASIC: Human Insight and Trust




## Technology Development Plan (FY)




## Description

Research **centered on human-machine teaming elements of trust calibration, transparency, and trust-based biases in humans-machine contexts.**

## Technology

- Human-machine teaming metrics/methods for evaluating trust, shared awareness/shared intent
- Design parameters for enhancing human-machine performance through transparency injects
- Quantification/validation of the impact of trust-based biases (e.g., suspicion) in cyber/ISR areas

**DELIVERING:** Design principles, assessment methodology, concept evaluation & testing

## Benefits to the Warfighter

- Validated design principles for fostering transparency in human-machine teaming contexts
- Validated assessment metrics and methods for human-machine teaming
- Identification of trust pedigree and other biases within A2AD and cyber operations
- Evaluation and assessment of fielded autonomy within Air Force platforms (e.g., Auto GCAS)

# Scalable Teaming of Autonomous Systems (STAS)

## Goals:

**Decentralized mission-level task allocation/assignment:**

- Collaborative ensembles easily tasked, and re-tasked with fast planning, under conditions of uncertainty & partial information.

**Robust self-organization, adaptation, and collaboration:**

- Dynamic adaption, ability to self-organize and dynamically restructure
- Robustness to addition and loss of agents
- Agent-to-agent collaboration.

**Space management operations:**

- Operation over diverse spatial areas, flexibly to adapt with distributed intelligence to update, within-mission boundaries, incorporating scalability, constraints and timelines for mission success..

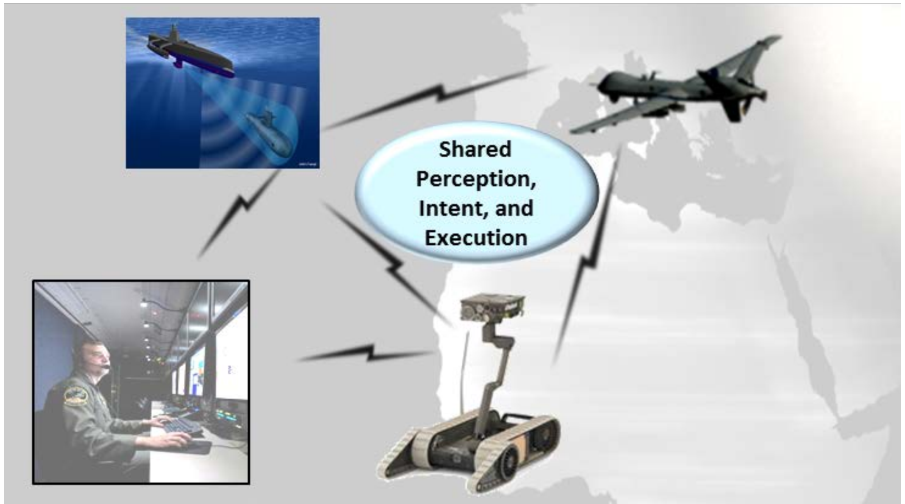
**Sensing/synthetic perception:**

- Distributed learning and sharing via a variety of sensing modalities seamlessly processed and fused
- Ability to overcome limited individual platform limitations, including distributed databases and scalable reach back

## Central Technical Challenge:

**Shared mission intent and execution, decentralized as well as collaboratively**

**Complex, Dynamic, Heterogeneous Teams**




**Co-Leads: Brian Sadler, ARL**
**Tom Wettergren, NUWC**

# Scalable Teaming of Autonomous Systems (STAS)

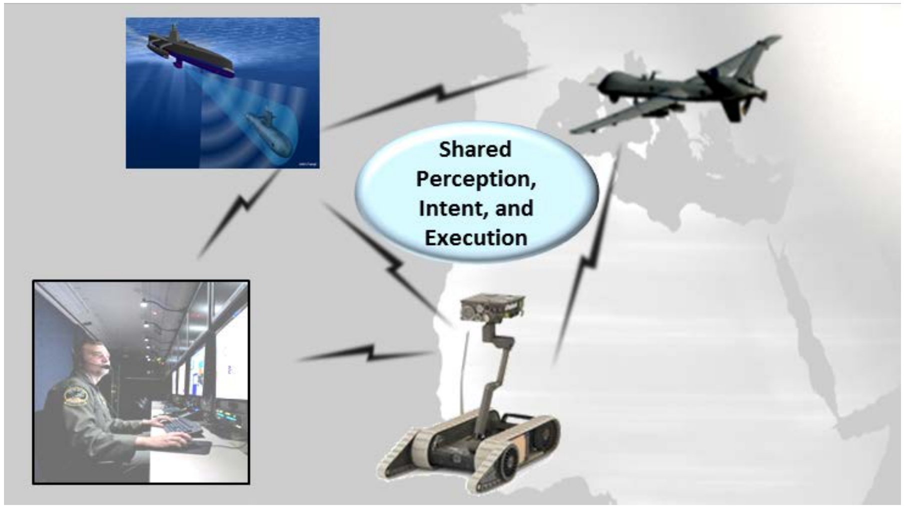
**Technology Trends:**

- Near Term
  - Proper use of heterogeneity in teams
    - Self-Organization
    - Optimize utilization of assets
  - Supervisory control of scalable teams
    - Balance between individual & team control
    - Hierarchy of control
- Far Term
  - Operations in Hazardous Environments
    - IED/Checkpoint Operations
    - Onboard ship firefighting
  - Logistics
    - Ground Convoys/Air-ground operations
  - Ballistic rate multi-agent operation
    - Smart munitions
    - Sensor delivery
  - Wireless network enhancement
    - Mobile base stations – air & ground

**Central Technical Challenge:**

**Shared mission intent and execution, decentralized as well as collaboratively**

**Complex, Dynamic, Heterogeneous Teams**

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# Scalable Teaming of Autonomous Systems (STAS)

## Hard Problems:

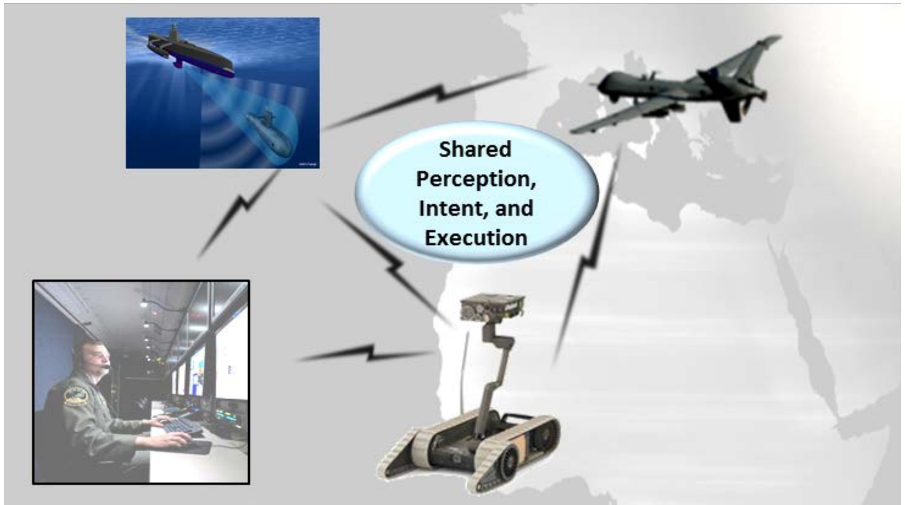
- **Scalable, self-organizing, organization appropriate to mission tasking:**
  - Robust to limited communications and uncertain or partially known information
  - Appropriate relationships between individual unit intelligence, team, coalition, and global
  - Handles intelligent adversaries.
- **Task allocation/assignment, planning, coordination & control for heterogeneous systems**
  - Tasks have spatial/temporal dependencies w/ logical constraints on vehicles & tasks
  - Structuring on-board autonomy to balance multiple competing and conflicting performance metrics, and individual platform vs. group objectives.
- **Space management permitting operation in close proximity to other manned & unmanned systems including crowded military & civilian areas**

**Requires rigorous methods & tools for predicting behaviors and field testing approaches to identify potential problems & prove system robustness**

## Central Technical Challenge:

**Shared mission intent and execution, decentralized as well as collaboratively**

**Complex, Dynamic, Heterogeneous Teams**

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# STAS: Naval Science of Autonomy

Studying collective motion & decision-making in fish (left) as inspiration for robust UUV collaboration experiments (right), N. Leonard & I. Couzin, Princeton University

**Description:** Multi-disciplinary research in new methods/principles /frameworks for
- Scalable, self-organizing, survivable, organizational structure/hierarchy of heterogeneous UxVs appropriate to naval mission domains
• Intelligence enablers/architectures for unstructured, dynamic, and uncertain naval environments
• Human interaction/collaboration for hybrid human/autonomous teams
• Perception-based control & decision-making for exploration and exploitation of naval environments

## Recent Accomplishments

•Multi-robot methods that exploit ocean dynamics/models and support improved predictive capabilities of the maritime environment
•Models of collaborative behaviors in animals and use as inspiration for new autonomy methods/principles
•New results on the role of information in multiagent coordination, leveraging control and game theory
•Human interaction experiments/concepts with large numbers of systems, swarms, bio-inspired, decentralized
•Methods for machine learning of autonomy for the current mission based on prior mission experience

## Approach:

• Develops collaborations between researchers in different disciplines that have traditionally been somewhat separated: engineering (air, sea, undersea, ground), control theory, computational intelligence, human factors, biology, economics/game theory, cognitive science/psychology, physics, applied mathematics, & neuroscience

•Focuses on making progress on a set of cross-ONR autonomy technical challenges identified and regularly updated in a series of ONR/NRL workshops with the broader community

# Test and Evaluation, Validation and Verification (TEVV)

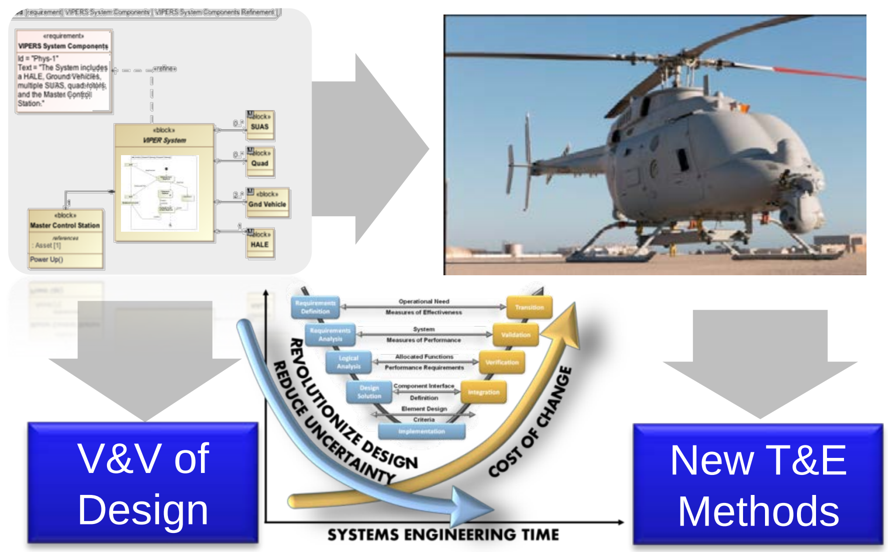
## Goals:

- **Methods, Metrics, and Tools Assisting in Requirements Development and Analysis:**
  - Precise, structured standards to automate requirement evaluation for testability, traceability, and consistency
- **Evidence-Based Design and Implementation**
  - Assurance of appropriate decisions with traceable evidence at every level to reduce the T&E burden
- **Cumulative Evidence through Research, Development, and Operational Testing:**
  - Progressive sequential modeling, simulation, test, and evaluation to record, aggregate, leverage, and reuse M&S/T&E results throughout engineering lifecycle
- **Run-time Behavior Prediction and Recovery:**
  - Real time monitoring, just-in-time prediction, and mitigation of undesired decisions and behaviors
- **Assurance Arguments for Autonomous Systems:**
  - Reusable assurance case-based on previously evidenced “building blocks”

## Central Technical Challenge:

**From algorithms to scalable teams of multiple agents – Developing new T&E, V&V technologies needed to enable the fielding of assured autonomous systems**

## Reliable and Trustworthy Systems:




**Co- Leads: Jeffrey DePriest, DTRA**
**Matthew Clark, AFRL**

# Test and Evaluation, Validation and Verification (TEVV)

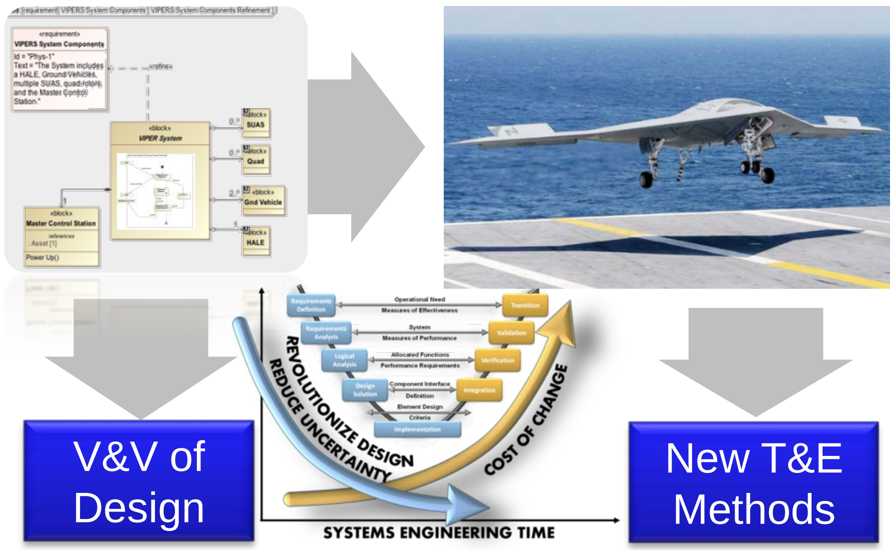
## Technology Trends:

- **Near Term:**
  - M&S and T&E capabilities not integrated for near term autonomy based systems
  - Limited V&V capability within the research domain tailored / configured for autonomy
  - OSD seedling autonomy licensure effort
  - Coordinated strategy identifying relevant goals, V&V capabilities, and future T&E infrastructure
- **Mid Term:**
  - Re-vamp formal methods to generate traceable evidence from requirements to design
    - Leveraging capabilities from Cyber Sec COI
  - Generate standard metrics for evaluating Aut Sys.
  - Improving M&S and T&E re-use
  - Demonstrate semi-autonomous hardware in the loop
- **Far Term:**
  - Demonstrate combined evidence from design to integration to test of a fully autonomous system
  - Assurance from run time constrained behavior
  - Develop an integrated assurance argument

## Central Technical Challenge:

**From algorithms to scalable teams of multiple agents – Developing new T&E, V&V technologies needed to enable the fielding of assured autonomous systems**

## Reliable and Trustworthy Systems:

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# Test and Evaluation, Validation and Verification (TEVV)

## Hard Problems:

### State-Space Explosion

- Algorithmic decision space is complex, adaptive, and cannot be exhaustively searched, examined, or tested

- **Unpredictable Environments:**
  - Autonomous systems operate in unknown, untested environmental conditions
  - Autonomous systems are difficult to assure correct behavior in a countless number of environmental conditions
- **Emergent Behavior**
  - Interactions between systems and system factors may generate unintended consequences
  - Autonomous systems are difficult to sufficiently capture and understand all intended and unintended consequences
- **Human-Machine System**
  - Handoff, communication, and interplay between operator and autonomy are key enablers for the trust and effectiveness of an autonomous system

## Central Technical Challenge:

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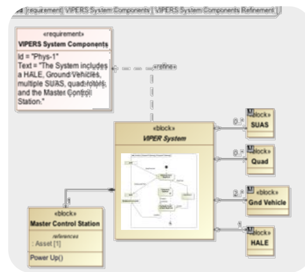
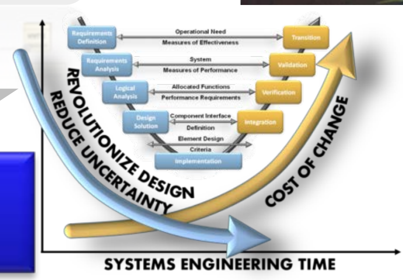


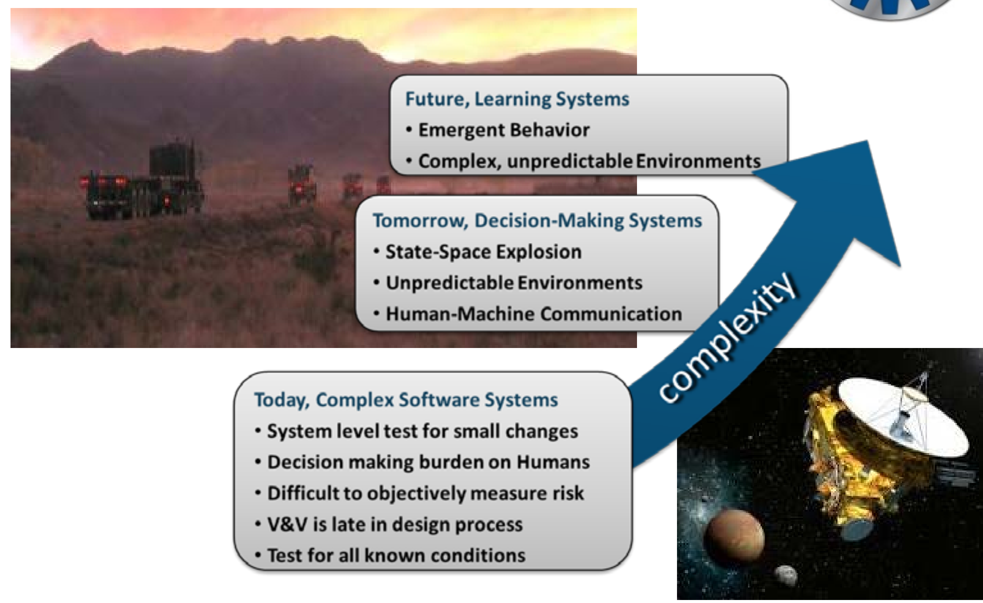
V&V of Design




New T&E Methods

**Co- Leads: Jeffrey DePriest, DTRA**
**Matthew Clark, AFRL**

# TEVV: Pedigree-Based Training and Licensure




## Objectives:

- Provide insight to DoD SMEs about the challenges associated with the autonomous systems training and licensure scheme
- Investigate current processes for training autonomous system operators, identifying requirements for documenting the "pedigree" of a learning algorithm as it relates to the "pedigree" or "competency" of a human operator
- Identify the technology gaps to be addressed should a certification approach be pursued w/i DoD

## Operational Opportunities:

- Establishes a rigorous Testing, Evaluating, Verifying, and Validating (TEVV) process for future autonomous systems
- Measures the ability of new technologies to operate in dynamic, complex, and/or contested environments
- Establishes a comprehensive strategy that addresses both technical factors and current policy mandates

## Technical Challenges:

- Provide critical information on the benefits and issues associated with pursuing a task-based licensure strategy for certifying autonomous technologies
- Guide future actions of the TEVV Working Group
- Share information with industry and academia to continue the dialog with key DoD technology development partners
- No plans to conduct further studies on this subject after this study is completed

# Autonomy Research Pilot Initiative

Technical Readiness Level
(Approx. range 3 to 5)

*Lower* → *Higher*

- Exploiting Priming Effects in Autonomous Cognitive Systems
- A Privileged Sensing Framework
- Autonomy for Adaptive Collaborative Sensing
- Autonomous Squad Member
- Autonomy for Air Combat Missions
- Realizing Autonomy via Intelligent Adaptive Hybrid Control
- Collective Defeat of Hard and Deeply Buried Targets

TARDEC

NAWC

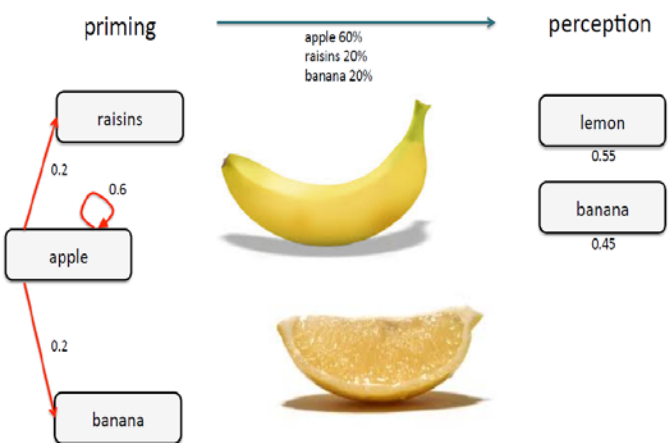
SPAWAR

**Human/Autonomous System Interaction and Collaboration**

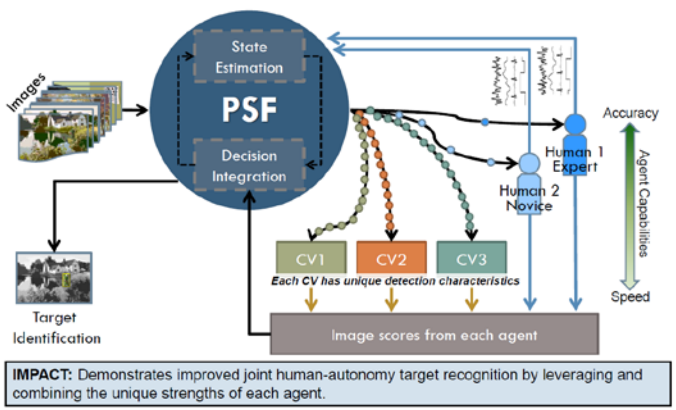
**Machine Perception, Reasoning, and Intelligence**

**Scalable Teaming of Autonomous Systems**

# Autonomy Research Pilot Initiative

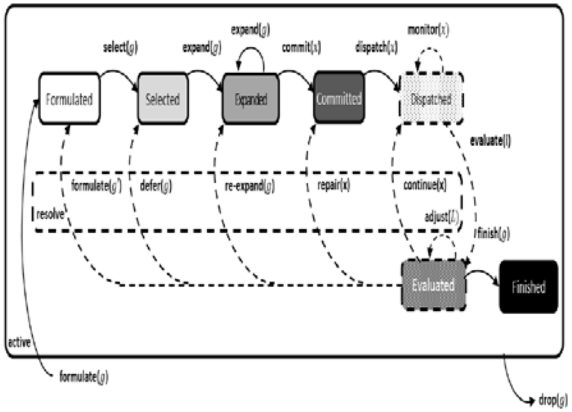



- **Exploiting Priming Effects Team (Navy)**
  - Develop machine perception relatable to the manner in which a human perceives the environment
  - *Combined 3D segmentation of objects & aligned consecutive frames by factoring in robot's/camera's motion to improve performance of 3D segmentation*
  - *Testing priming and context approaches on realistic NYU-developed RGB-D datasets – anticipate 8% improvement in recognition rates*




- **Privileged Sensing Network Team (Army)**
  - Improved integration of humans into the human-machine team
  - *Developed a principled approach to multi-scale integration incorporating confidence in human performance and consequence of task outcomes to enhance human-autonomy integration*
  - *Developing testbed technologies and preliminary measurement techniques to estimate changes in operator trust-in-autonomy on the basis of behavioral decisions and physiological signals*

# Autonomy Research Pilot Initiative

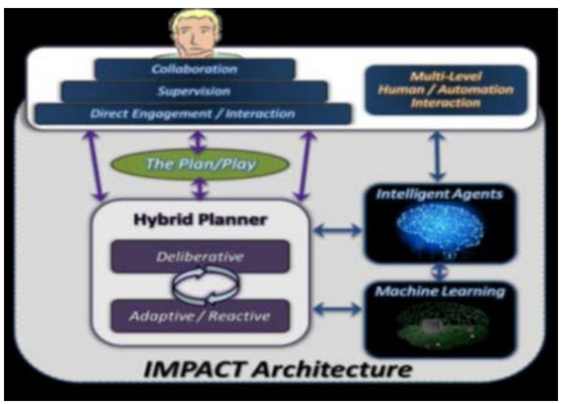



- **Autonomy for Adaptive Collaborative Sensing (AF)**
  - Develops intelligent ISR capability for sensing platforms to have capability to find & track targets
  - *Established Situated Decision Process (SDP) architecture, components, and interfaces; integrated system and performed initial simulation and live testing*
  - *Working towards demonstration of fully autonomous (no user interaction required) decentralized control of three small UAVs and their sensors performing a collaborative search and track mission*

- **Autonomous Squad Member (Army)**
  - Integrates machine semantic understanding, reasoning, and perception into a ground robotic system
  - *Early implementation of a goal reasoning model, Goal-Directed Autonomy (GDA) to provide the robot the ability to self-select new goals when it encounters an unanticipated situation*
  - *Continue to develop and test transparency concepts that enable human team members to understand an intelligent agent's intent, performance, future plans and reasoning processes.*

# Autonomy Research Pilot Initiative


- **Autonomy for Air Combat Missions Team (AF)**
  - Develops goal-directed reasoning, machine learning and operator interaction techniques to enable management of multiple, team UAVs
  - *Developed a novel differential game formulation for multi-vehicle intercept problem which can be applied to cooperative aircraft defensive tactics*
  - *Developing the Pilot Vehicle Interface (PVI) and autonomy technology for control of an Unmanned Wingman UAV in a virtual cockpit simulation*



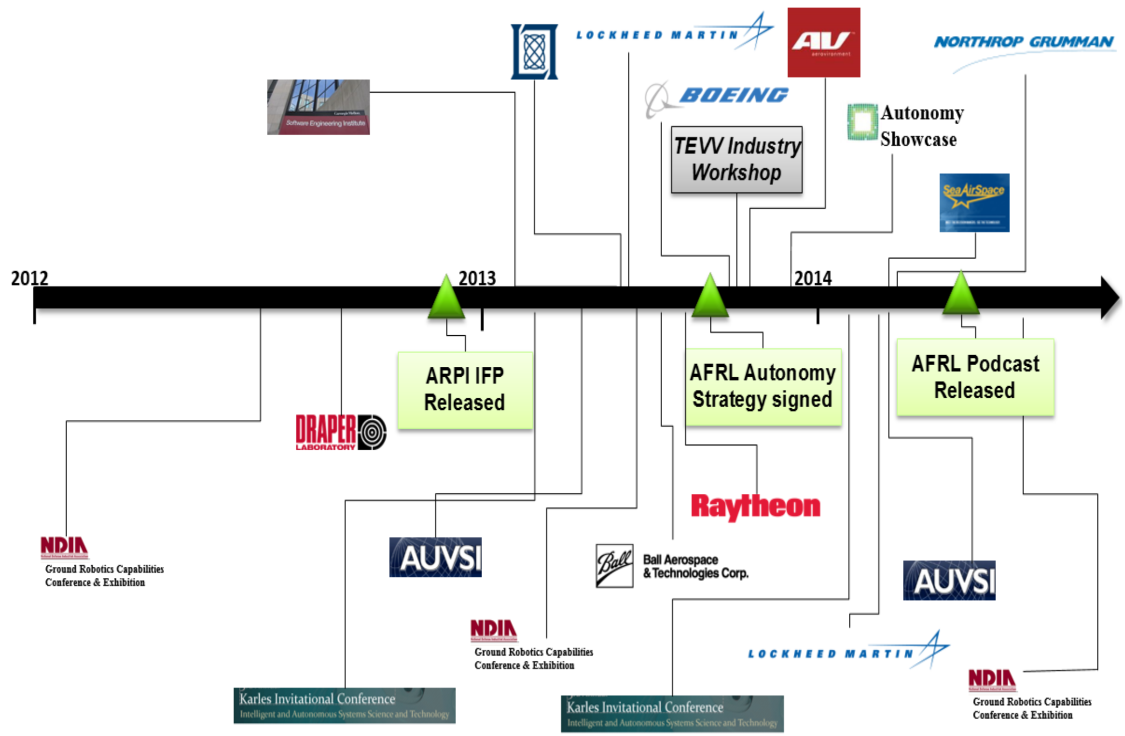

- **Realizing Autonomy via Intelligent Adaptive Hybrid Control (AF)**
  - Develops a flexible UAV operator interface enabling operator to “call a play” or manually control the system.
  - *Established a virtual laboratory with common research testbed across AFRL, ARL, SPAWAR, and NRL & designed display and control interface concepts to support both high-level tasking and detailed tailoring of automated plays*
  - *Integrating mulit-UxV cooperative planning with intelligent agent reasoning and enhanced/intuitive human-autonomy dialog capabilities to supervise multiple UxV’s conducting base security missions*

# Enduring Gaps for Autonomy

- Open, cognitive architectures that facilitate interaction between intelligent systems and human
- Planning and reasoning for dynamic, uncertain operational and physical environments
- Concepts for decentralized perception, planning, and collaboration among large groups of heterogeneous, autonomous agents
- Robust supervised and unsupervised learning
- Natural, intuitive communications between humans and intelligent agents/systems
- Creation of "common ground" and communicating intent (abstract reasoning)
- Means for assessing the safety and performance of systems that learn and alter behavior over time

# How You Can Help
# Industry Engagement Opportunities

- **Partner with the DoD labs to develop both technology and methodologies/ concepts as part of an open architecture**
- **Provide independent experience (performance) and data**
- **While the Department is focused upon the solution of specific military problems, the technology has applicability well beyond the department, as evidenced by recent interest from non-defense based organizations.**




- **Defense Innovation Marketplace – centralized, online resource for potential market researchers to learn about Department of Defense (DoD) S&T/R&D investment priorities, capability needs and technology interchanges.**