Autonomy &
Autonomous Unmanned Systems
Overview, Investment Approach, and Opportunities

for
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National Academy of Sciences

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Intelligent Unmanned Systems

The Imperative

WHY Pursue Intelligent UxS?

- "It is not the strongest nor the most intelligent that survives; it is the one that is the most adaptable to change." (Darwinian consequence)
  - Intelligent autonomy facilitates: Adaptation in unpredictable worlds, adaptation at machine speed, adaptation given overwhelming data

Therefore…

- We must seek disruptive gains in
  - Detect-to-Engage Sequence
  - Operational Tempo
  - Survivability
  - Capacity
  - Operational Readiness

Improve today's missions
Enable tomorrow's missions

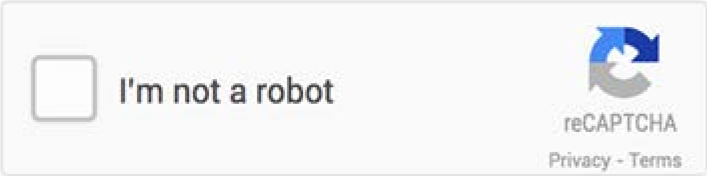
Intelligent Unmanned Systems

WHAT Should We Do?

To Achieve these Disruptive Gains, We Must:

- Leverage **unmanned** to increase scale & consistency while decreasing risk and size
  - Reliability vs "Attritability" or Disposability
- Leverage **autonomy & AI** to make machines and UxS intelligent
  - Proficient in worlds that are: Unpredictable, data-saturated, and/or operate at machine-speed
- Leverage in-theater **learning** to make machines and UxS better with experience


A 2,018 drone Intel lightshow



Intelligent Unmanned Systems

HOW Can We Get There?

As a <u>Community</u>, we will collaboratively attack the following:

1. Development (broad yet intentional)

- What specific capabilities must our intelligent machines and UxS posses
  - S&T as a pipeline (6.1 to 6.4+)
  - Warfighting / Naval Unique Needs
- What roles will humans vs machines play
- What is the path to trust
  - Individual, institutional, coalition, machine-to-human, etc.

2. Alignment

- Achieve coherence in goals and actions between the various communities
  - Technically & programmatically
  - Legal, moral, and ethical (vis-à-vis the broader community)

3. Impact

- Make our efforts concrete, actionable, and impactful
  - Near-term & long-term
  - Transition, operationalization, and fielding (not demo only)

Questions

It is not the strongest nor the most intelligent that survives.
It is the one that is the most adaptable to change.

—A core principle from Charles Darwin's
On the Origin of Species

Image from lecture by: Tony Seba, Stanford Univ. Oslo, NOR, Mar 2016

Preliminaries

Clarification of Terms

Unmanned (Automated) Systems

- What is it: Removing or remotely locating the human
- Why do it:
  - To reduce cost, size, etc. (e.g., by removing life support)
  - To remove risk to life
  - To achieve consistent & repeatable performance

Autonomous Systems

- What is it: Interactively adapting to the world
- Why do it:
  - When the world can't be sufficiently specified a priori
  - When adaptation must occur at machine speed

Learning Systems

- What is it: To improve performance with experience
- Why do it:
  - Much knowledge is not explicitly available / represented, evolves rapidly, or lives in large data sources / decision spaces

Artificial Intelligence

- **AI enables significant autonomy**
- **AI includes learning, reasoning, introspection, etc.**

Note: None of these three are *necessarily* dependent on the other two

Preliminaries

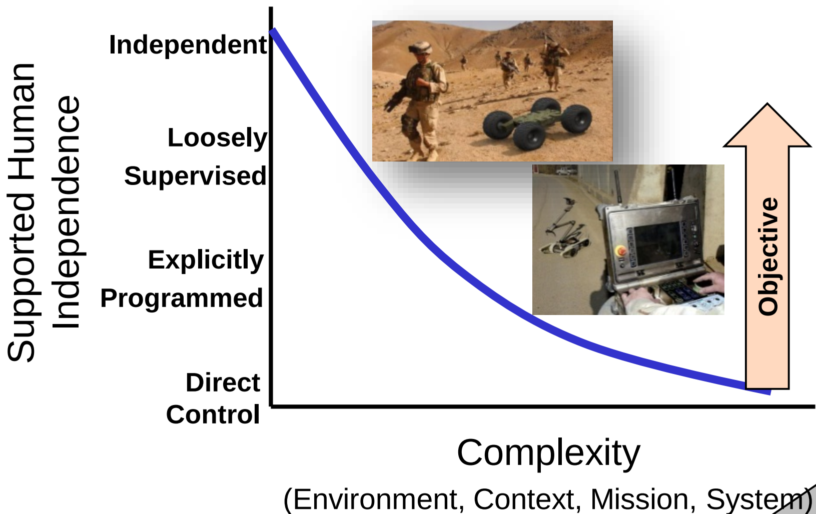
Two Roles of Machine Intelligence

There are *two* human-machine relationships that depend on mission context:

- Optimize human (or hybrid team) performance
- Minimize reliance on humans

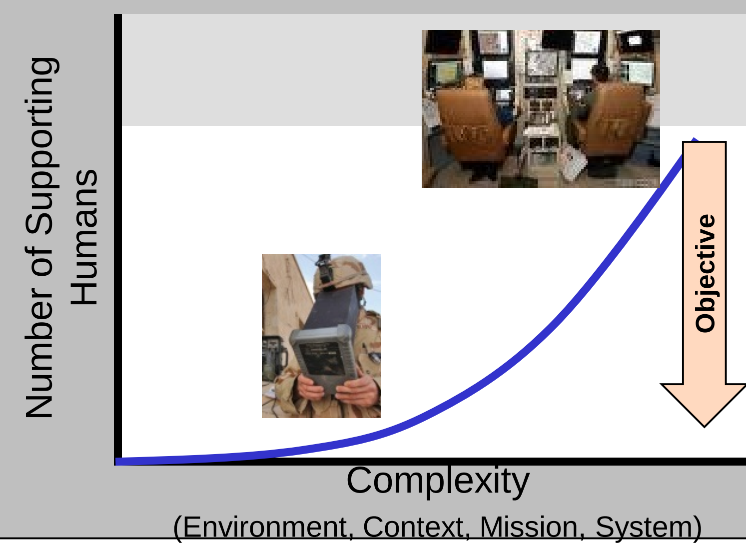
Both are valid—the machine intelligence must account for this difference

Human is *Supported*



Goal
Minimize human "control"
Optimum Level
Mission dependent

Human is *Supporting*



Goal
Minimize supporting humans
Optimum Level
Zero

Preliminaries
Quantification of Autonomy

Abandon efforts to *quantify* autonomy

- "Defining levels of autonomy is not useful" --US DoD Defense Science Board, www.acq.osd.mil July 2012
  - e.g., when has the "level of autonomy" been used to describe a human's role?
- A simple quantification scheme for autonomy is not possible
  - The dimensions of autonomy numerous and do not form a proper metric space; therefore, simplifying to a 1-dimensional scale is not possible

Instead focus on:

- Articulation of what capabilities are / should be provided by autonomous systems
- Identification of what is delegated to human vs machine
- Building trust (e.g., transparency into machine, understanding of performance, proper user experience & use cases, etc.)

Trust & Reliance in Autonomy

Goal

- Develop autonomy to enable systems that the warfighter can appropriately rely on (avoid misuse, mistrust, & disuse)

Foundations of Reliance & Trust

- Trust (an attitude) drives reliance (a behavior) in complex & dynamic applications where exhaustive evaluation of options is not possible

Types of Trust

- Individual Trust *(Will the operator use it?)*
- Institutional Trust *(Will the establishment accept and procure it?)* ← **Must appropriately balance procurement risks with rapidly achieving operational impact**
- Coalition Trust
  (Will one nation's systems follow another's Rules of Engagement?)
- Machine Trust in Humans
  (Will / should machines trust humans that have degraded / incorrect situational awareness?)

All facets of trust must be addressed to succeed

Government & Industry

Investments Focus

S&T Development Pipeline

- Science-to-Technology is best envisioned as a **pipeline**
  - NO innovation occurs “out of thin air”
  - Industry’s rapid innovation and progress is founded on ***decades*** of government-funded basic and early applied research
- ONR (et al) funds performers that found or concurrently staff top industry or high-tech startups in the areas of autonomy and machine intelligence
- Result = Healthy and productive symbiosis between the DoN and Industry…

Government vs. Industry Divergence

- DoN must ask:
  1. What is the technology’s purpose?
  2. Will Industry ever invest in or adjust for that / can we leverage?
- This results in Naval Unique Needs

DoN S&T is part of the engine driving the Industrial Ecosystem in S&T

Naval Unique Needs

Uniquely Naval Mission Attributes
• Execute or disrupt detect-to-engage sequence, kinetic / non-kinetic effects
• Non-permissive, adversarial, covert, or clandestine
• Dynamic, unstructured, uncertain, or harsh environments
• Force multiplication, high-tempo, or disposable / atritable

Common Drivers Requiring Unique Military Advances
• Long duration, large standoff, or disadvantaged communications / navigation
• Scalable, distributed, or decentralized adaptation
• Workload or manning reduction, employment by non-specialist
• Rapid human-machine information exchange
• Cross-domain (e.g., air-water)
• In-mission goal arbitration

Uniquely Naval (Military) Attributes of Data

- Industry typically has copious, rich, labeled datasets in human-understandable modalities (e.g., imagery, video, text, etc.)
- DoN typically has copious "target-poor" datasets that include traditional + non-intuitive modalities (e.g., hyperspectral, sonar, magnetics, etc.)
  - This is a critical distinction for much in Autonomy & AI (e.g., Deep Learning)

S&T Investment Strategy

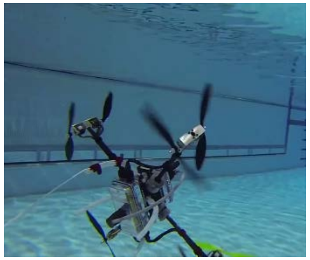
Autonomy & Autonomous Unmanned Systems

WHAT we Seek to Achieve

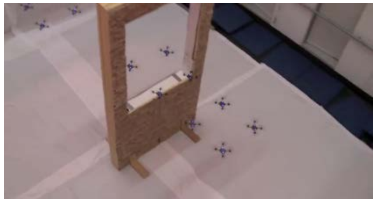
- **To substantially improve naval power:**
  - Increase: Lethality, survivability, capacity, operational tempo

WHO we Serve

- **The Warfighter of Today**
  - Substantially increase capability & capacity for today's missions
- **The Warfighter of Tomorrow**
  - Enable fundamentally new capabilities & missions not possible today





HOW we will Succeed

- Appropriately teamed with humans
- Address all facets of trust
- Enterprise-wide teaming on **transition, operationalization, and fielding**:
  - Balance risk vs. time-to-field
- Broad basic research program (Sci. of Autonomy)

Key Attributes

- Multi-domain, heterogeneous, scalable
- Long duration, robust, persistent
- Learning
- Distributed, collaborative
- Full-spectrum of human-machine interdependence
- Address Naval Unique Needs

DoN Investment Approach

Applied Autonomy

- Investment by Area
  - Naval Mission Autonomy
  - Naval Platform Autonomy
  - Cross-Application Enabling Autonomy
- Investment by Risk
  - Disruptive—Innovative Naval Prototypes (INPs)
  - Evolutionary—Future Naval Capabilities (FNCs)
- Investment by Focus
  - Substantially advancing the tech
  - A user of state-of-the-art (requiring additional development)
  - A user of state-of-the-practice

Supporting Efforts

- Lethal Autonomous Weapons Systems (LAWS)
  - 3000.09 Policy Implementation / update
- COTS UAS Ban Process

Investments & Opportunities

Science of Autonomy

Human Collaboration

- Roles
  - Improving human-autonomy function division and relationships/roles
- Communication
  - Improving human-autonomy interaction
  - Comprehension
- Improving human-autonomy comprehension

Scalable Robust Collaboration

- Self-organizing structure/hierarchy appropriate to mission
- Scalable – Simple individuals with minimal communications lead to versatile group
- Rigorous mathematical methods and tools for designing & predicting behaviors

Perception & Intelligent Decision Making

- Broader Mission/Environment Understanding
- Robustness in Naval Environments
- High Speed Control/Decision-Making, Rapid Adaptation/Learning

Intelligence Enablers & Architectures

- Integrated Architectures
  - High Level Intelligence with Flexible Behaviors/Perception
- Learning & Reasoning
  - Complex relationships, tasks, group behaviors
- Long Duration Missions
  - A priori mission/environmental assumptions become invalid

Investments & Opportunities

Naval Mission Autonomy

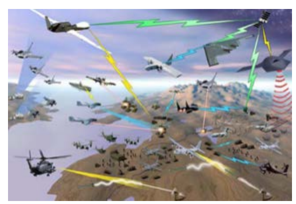
Goal

- Develop autonomy as an enabler to increase the capability and capacity of naval missions and supporting functions while improving risk to mission, risk to life, and operational tempo

Missions & Support Functions of Interest

Anti-Air, Submarine, & Surface Warfare

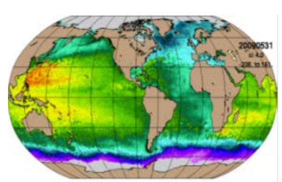
Expeditionary, Urban, & Security Operations



Strike, Electronic, Mine, and Counter-Unmanned Warfare

Logistics, Evacuation, Lighten the Load

Arctic, Space, Cyber



And New Missions Not Possible Today

Future Research Directions

- Larger operational areas / longer duration with many inexpensive UxS
- Increasingly automated shipboard operations with fewer personnel and sustained maintenance and safety
- Operations in complex & GPS degraded environments with inexpensive / low SWAP sensing
- Manned / unmanned teaming
- Exploit the ocean environment to our tactical advantage
- Predictive capabilities at tactical and strategic scales
- Temporally non-myopic planning & replanning

Investments & Opportunities

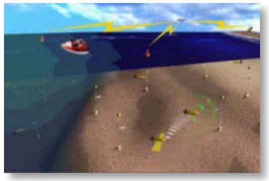
Naval Platform Autonomy

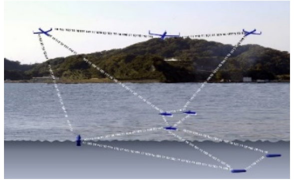
Goal

- Enable autonomous unmanned systems to operate in increasingly dynamic, unstructured, uncertain, and/or adversarial environments while improving warfighting impact across all domains and phases of operations

Domains of Interest

- Physical
  - Air, surface, undersea, ground, space
  - Arctic, urban, etc.
- Multi-Domain
  - Composable / configurable systems exploiting multiple physical domains
- Cross-Domain
  - Capability to work effectively **across** physical domains





Future Research Directions

- Improved perception and situational awareness
  - Intent determination, activity recognition and motion prediction
  - Perception in highly cluttered environments and of intermittent or occasionally occluded phenomenon / targets
- Improved decision making
  - Efficient and effective selection of multiple competing objectives
  - Cooperative decision-making with accurate and fast sensor fusion
  - Perceive environment and respond effectively to dynamic situations
- Tighter coupling between automated perception and autonomous platform behaviors
- Affordability and modularity for current and future fleet vehicles
- Autonomous launch & recovery in austere environments

Investments & Opportunities

Cross-Application Autonomy Enablers

Goal

- Advance the foundations of autonomous unmanned systems to achieve
  - Flexible human-machine teaming with agile interdependence
  - Persistence, scalability, and affordability
  - Trust, rapid concept development / testing, and disruptive employments

Foundations of Interest

- Human / Unmanned Systems Collaboration
- Perception & Intelligent Decision Making
- Scalable & Robust Distributed Collaboration
- Intelligence Enablers & Architectures

Future Research Directions

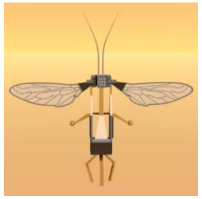
- Human-machine teaming
  - Supervisory human interaction with large numbers of heterogonous systems
  - Rich and rapid between-sortie knowledge exchanges
  - Increased operational envelope & tactical role with greatly reduced need for human intervention or supervision by non-experts
- V&V for both safety & mission competence
- Increasingly sophisticated collaboration across multiple heterogeneous platforms
- Enable extended duration missions
- Disposability & atritability
- Cybersecurity & counter-unmanned systems
- Trust & reliance

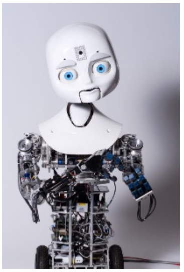
Investments & Opportunities

Novel Autonomous Platforms

Goals

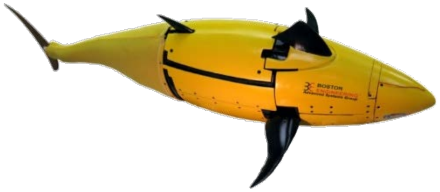
- Novel Undersea Vehicles that are stealthy, highly efficient, highly maneuverable vehicles – exceeding current engineering
- Novel Air Vehicles that are capable of agile maneuver through clutter - under tree canopy, inside buildings & ships
- Humanoid Robots as teammates capable of dangerous missions (fire fighting, building recon) and relieving sailors of time-consuming low-level tasks (maintenance inspection, roving watch)





Future Research Directions

- Closed loop control using biosensing (optic flow, biosonar, electrosense, lateral line) and interactive perception (undersea and air)
- Fundamental understanding of the hydrodynamics of high efficiency bio-inspired underwater propulsion
- Compact, low power perception and mapping for nano-UAVs
- Muscle-like actuators and multifunction material control surfaces (undersea and air)
- Natural human robot interaction (natural language, gesture)
- Higher level control of reaching, grasping and manipulation (humanoid, undersea)



Opportunities

Autonomy & AI, Unmanned Systems

Transition, Assimilation, and Fielding

- Not only “transition”; not only “experimentation”
- Is actually *different and more challenging* here
  - – Requires full DOTMLPF consideration
    - – Why? Involves new (yet untrusted) technology + new user experience / use case
  - – Can be instantiated in virtually infinite forms
    - – i.e., what’s needed = f(what’s possible) = f(what’s needed) = …

Way Ahead (partial)

- Need principled and intentional approach to transition, assimilation, and fielding
  - – Need tighter-than-normal feedback between users & developers:
    1. What capabilities do we give to the machine?
    2. What are roles of machine vs human?
    3. What is the path to trust?

- We do have successes! (e.g., smaller more agile communities)
  - – How to scale those to the broader DoN

Opportunities & Imperatives

Autonomy & Unmanned Systems

Imperatives for Success

- Transition, operationalization, and fielding
- Incorporate learning (in situ)
- Scale → Reliability vs. Atritability vs. Disposability
- New employment concepts and all domains
- Integrate with cyber

Research Opportunities

- See following slides

Autonomy & Weapon Systems

Overarching Context

Policy

- The United States has policy for **all weapon systems** to ensure legal & ethical employment
  - Law of Armed Conflict: Distinction, Proportionality, & Military Necessity

- Decisions to use lethal force are made by humans at the appropriate level of command based on military result and risk

- Weapon systems employing autonomy and automation are governed under exactly the same framework of legal and ethical concerns

Challenge

- As more advanced autonomy and artificial intelligence emerges, further thought and clarification is needed to ensure the nature of the ***technology & usage*** remains legally & ethically consistent

Autonomy & Weapon Systems

Policy Overview: DoD Directive 3000.09

Key Policy Tenets

- In the United States, the key tenet is that weapons systems shall be designed to allow commanders and operators to **exercise appropriate levels of human judgment** over the use of force
- A key point at which this judgment must be exercised is during the **target selection process**
- Purpose is to minimize risk (probability & consequence) of unintended engagements

Categories (specified in DoDD 3000.09)

- *Semi-autonomous* = A human performs target selection
- *Autonomous* = A machine performs target selection
- *Human-supervised autonomous* = Autonomous but a human can intervene to limit the amount of unacceptable damage

Current DoD Policy:

- Allowed under standard DoD policy and processes:
  - Semi-autonomous lethal
  - Autonomous non-lethal
  - Human-supervised defensive anti-material
- Requires special review per 3000.09
  - Autonomous lethal (but no reviews requested to date)

Backup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ADAPTATION
THE BAD NEWS IS ROBOTS CAN DO YOUR JOB NOW. THE GOOD NEWS IS WE'RE NOW HIRING ROBOT REPAIR TECHNICIANS. THE WORSE NEWS IS WE'RE WORKING ON ROBOT-FIXING ROBOTS- AND WE DO NOT ANTICIPATE ANY FURTHER GOOD NEWS.

ONR Portfolio

Science of Autonomy and Science of AI

Science of Autonomy

Focuses on unique problems of physical systems that sense, interact, and adapt to deal with uncertainty, surprise, and change in the naval environment

- AI is one enabler of autonomy
- Also enabled by theories of regulatory systems/cybernetics to match behavior against the environment (e.g., control theory, systems biology, information theory, game theory/economics)
- Bio-inspiration for different levels of perceptual/behavioral capabilities
- Autonomy evolves concurrently with its physical embodiments: their form, functions, and affordances
- Autonomy works hand-in-hand with the sciences of the naval environment – oceanography, geoscience, littoral, atmospheric

Science of AI

Focuses on the breadth of decision-making, reasoning, understanding, and intelligence required across many naval problems

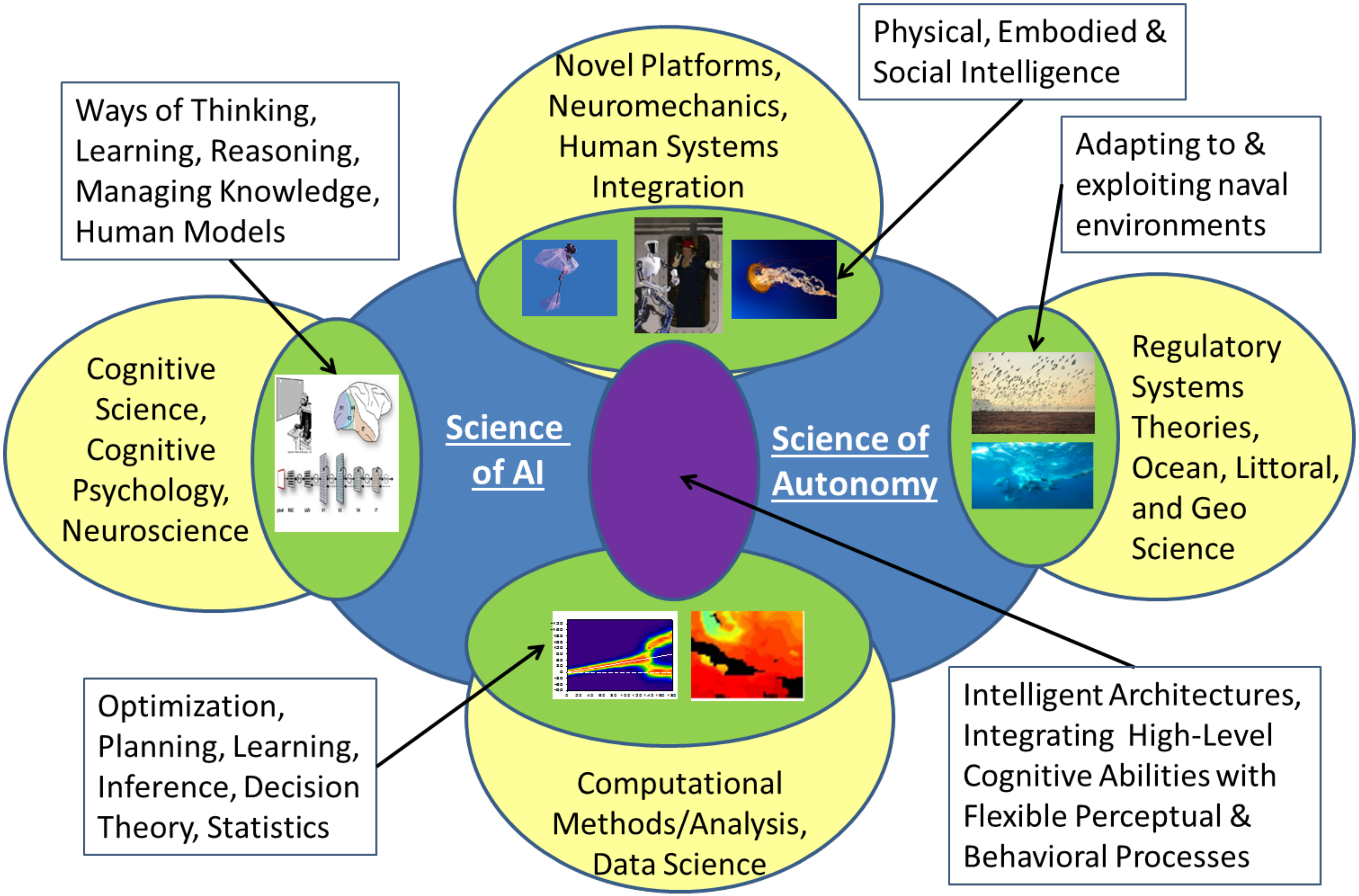
- Large quantity and diversity of data and knowledge across potential DoN applications driving knowledge representation, management, deconfliction
- Richer and deeper models of cognition and reasoning
- Increased understanding and modeling of human intelligence particularly
- Great variety of learning mechanisms and integration with domain knowledge
- Distributed AI, Machine-to-Machine Intelligence
- Hardware to accelerate Naval AI systems

Naval Research Enterprise

AI Taxonomy

Reasoning	Generation of inferences based on data, knowledge and context
Human-Inspired Intelligence (understanding and modeling)	Algorithms and architectures that are derived from human cognitive processes, and emulate them
Machine Learning	Algorithms and architectures that autonomously learn patterns in data or can be trained to learn a task
Perception	Algorithms and architectures developed to perform feature analytics of complex sensor data and to classify, identify and infer intent of entities and recognize situations
Collaboration, Interaction, and social intelligence	Interfaces that enable effective collaboration between warfighters and intelligent systems
Planning	Algorithms and architectures that support the development and selection of courses of action
Machine-to-Machine Coordination and Distributed Intelligence	Algorithms, communication protocols and architectures that enable distributed interactive analysis, reasoning and decision-making
Knowledge Representation and Management	Structuring data, knowledge, beliefs and uncertainty to support inferences that may not be explicitly stated within data, and then perform tasks or operations based on those inferences

Autonomy vs Artificial Intelligence



Industry vs Government

Investments & Focus

Common Claim

- "Industry investment dwarfs government; therefore…"

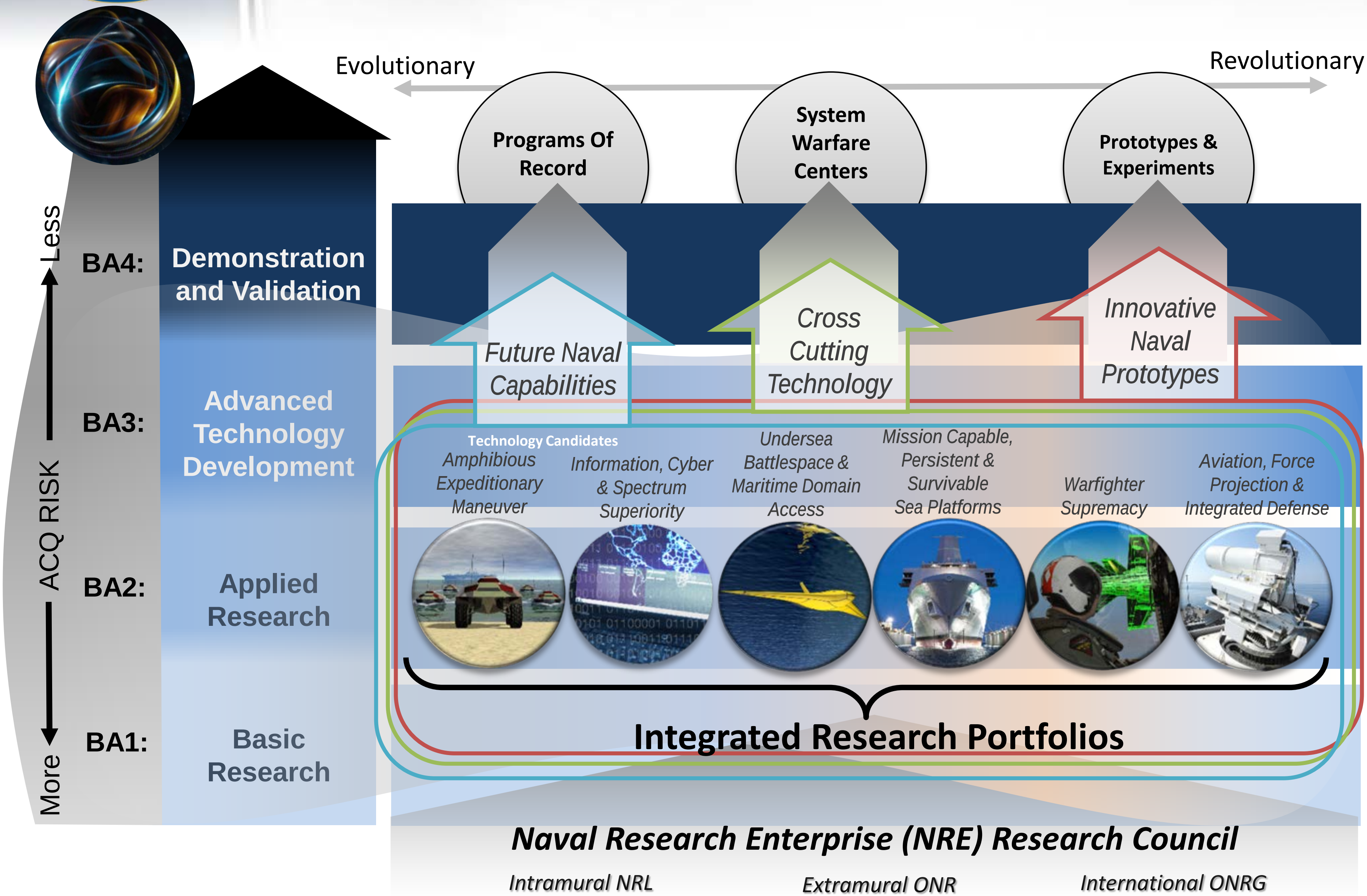
Unpack this observation

Sector	Investment Goals	Investment Time Horizon
Industry	Create competitive advantage / shareholder value	Short (some mid) term
Government	National security & public interest	Short, mid, **long** term

- Industry's rapid innovation and progress is founded on ***decades*** of government-funded basic and early applied research
  - NO innovation occurs "out of thin air"
  - Technology development is best envisioned as a **pipeline**

- Result = Healthy and productive symbiosis between the DoN and Industry…

Portfolio Director's Perspective



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