Naval Research Advisory Committee Report

How Autonomy Can Transform Naval Operations

October 2012

This report is a product of the Naval Research Advisory Committee (NRAC) Panel on *How Autonomy Can Transform Naval Operations.* The opinions, recommendations, and/or conclusions contained in this report are those of the NRAC Panel and do not necessarily represent the official position of the Department of the Navy, or the Department of Defense.

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Executive Summary

The Naval Research Advisory Committee was asked to study autonomy for the Navy after discussions with the ASN-RDA and OPNAV N2/N6 staffs in late 2011. In a compressed schedule of about four months, the autonomy Panel (a subset of the NRAC) met with over 80 subject matter experts and visited a number of organizations that focus on the study and application of autonomous systems.

The topic has been recently studied by the Defense Science and Naval Studies Boards as well as the CNO's Strategic Studies Group. This study corroborates their conclusions but with specific emphasis in two key areas. It was clear to the Panel that there are two essential keys to implementation of autonomy as a transformational capability: *build a community* and *build trust*. These themes led to the major recommendations of the report.

Autonomy is viewed here as a capability enabled by a set of technologies. When implemented, autonomy represents a transformational – and potentially disruptive – capability for the Naval Service. Unfortunately, the communities engaged in autonomous system research and development and acquisition are very diverse and distributed.

The level of autonomous system implementation will only be raised by intentional focus on autonomy as an overarching capability. An autonomy community, led by a senior advocate – as in previous "disruptive" Naval technology transformations – is essential to bring about this focus. This *Naval Autonomy Community* will facilitate strong cross-domain interaction – bringing technologists and Fleet operators together to identify Naval needs and work common technical challenges. The community will be able to identify synergies within and across domains and work to eliminate barriers to delivering autonomous systems to the Fleet.

The Panel found ample evidence that the autonomy domain is still significantly driven by technology "push". In order to create requirements "pull" and to ensure user adoption of autonomous systems, it is critical to build user trust. Trust-building begins in the design and development phases by requiring Fleet involvement throughout the development process – not just during the final stages of experimentation. If autonomous systems are to be accepted and used effectively, lifecycle support elements (e.g., manning, training and logistics) must be addressed in the design phase. Also, legal, ethical, safety and security issues must be considered very early in the process. Failing to address these issues can result in significant setbacks in fielding and acceptance of autonomy technologies.

There are four specific recommendations from the study:

1. Establish a Naval Autonomy Community – led by a senior champion – composed of technical, acquisition, requirements, and operational experts to <u>focus</u> on autonomy for Naval needs (Action: SECNAV/CNO),
2. Periodically commission an outside market survey to access, analyze and assess global autonomy markets that may be relevant to its efforts (Action: CNR),
3. Ensure that resource allocation reflects the urgency of introducing this capability to address Naval needs in key enabling technology areas. (Action: CNO N8 lead, CNO N2/N6 and CNO N9 support),
4. Develop protocols and enhance facilities as necessary to support autonomous systems testing and "trust building" (Action: CNO N84).

Panel Membership

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The NRAC Panel was composed of individuals with wide-ranging knowledge and experience in the military, government, industry, and academic domains.

Panel biographies are in Appendix A.

Terms of Reference Tasking

- **Examine the state of autonomy technologies and their potential to introduce new capabilities**

- **Identify classes of autonomy technology for Naval applications**

- **Identify critical barriers that impact employment of autonomy in Naval systems**

- **Recommend investments and developments to best leverage the use of autonomous systems**

The motivation for this study is the increasing demand for Naval forces to provide Global presence as well as to quickly respond to regional hotspots despite an increasingly constrained fiscal environment. The burden falls on the Navy to evolve and innovate for the future. The Navy's area of greatest challenge is the deployment of Anti-Access/Area Denial (A2AD) capabilities by nations and non-state groups. An important element for gaining area access and increasing the Fleet's capacity is through the force-multiplier of unmanned systems. Therefore, the development of autonomy and unmanned systems has been identified by Naval and DoD leadership as a high priority. However, specific pathways for the introduction of technologies that enable greater levels of autonomy have not been identified.

The objective of this study was to clarify the current and anticipated potential to transform Naval operations through autonomous systems. The study considered future Naval autonomy applications, with emphasis on maritime systems, and the challenges associated with this realization.

Specific tasking included:

- Define/characterize "autonomy" as applied to maritime systems and identify contributing technologies to autonomy capability,

- Identify classes of autonomy for military applications, including: Intelligence, Surveillance, and Reconnaissance (ISR), information management, decision making, logistics, weapon systems, etc.,

- Evaluate the global state-of-the-art (current and future) of autonomy,

- Review relevant technologies and ongoing Naval research and development of autonomy systems/subsystems,

- Identify critical issues/barriers that impact the employment of autonomy in maritime systems, including:
  - Technological
  - Environmental
  - Cultural
  - Affordability
  - International and domestic regulations/policy/doctrine
  - Department of Defense (DoD)/Department of the Navy (DON) acquisition process, and,

- Recommend technology solutions, investments and developments required to maximize the use of autonomous systems in the maritime environment.

The complete Terms of Reference are in Appendix B.

Who We Met

By design, the scope of the study was very broad – the Panel addressed the subject of autonomy as a set of enabling technologies – and not as just a group of platforms. During the four months of data gathering, the study plan included talking to over 80 experts in government, academia and industry. The complete list is in Appendix C.

To assess the state-of-the-art of autonomy research, the Panel sought out experts at major universities as well as in industry, government and ONR. They also met with Navy program managers and contractors who are developing or have fielded unmanned and autonomous platforms. The Panel visited with scientists and engineers at NASA's Jet Propulsion Laboratory (JPL) to learn from their long history of employing robotics in space. Office of the Chief of Naval Operations (OPNAV) and Fleet representatives provided feedback on the emergent requirements and challenges associated with the introduction of autonomous systems.

The Panel was well aware of recent studies on the subject of autonomy. All of the reports cited here conclude that unmanned and and/or autonomous systems have value in military operations and that coordination between the technical and operational communities would be beneficial. This report essentially confirms the findings of the previous studies and places emphasis on two major themes: *build a community* and *build trust.* These will be discussed throughout the report.

Reviewed studies were: Defense Science Board Study *Role of Autonomy in DoD Systems,* July 2012; Chief of Naval Operations Strategic Studies Group report *The Unmanned Opportunity*, January 2009; Naval Studies Board report *Autonomous Vehicles in Support of Naval Operations*, October 2005; Naval Research Advisory Committee Report *Undersea Maritime Domain Awareness,* September 2008; Naval Research Advisory Committee Report *Role(s) of Unmanned Vehicles (UV),* March 2003.
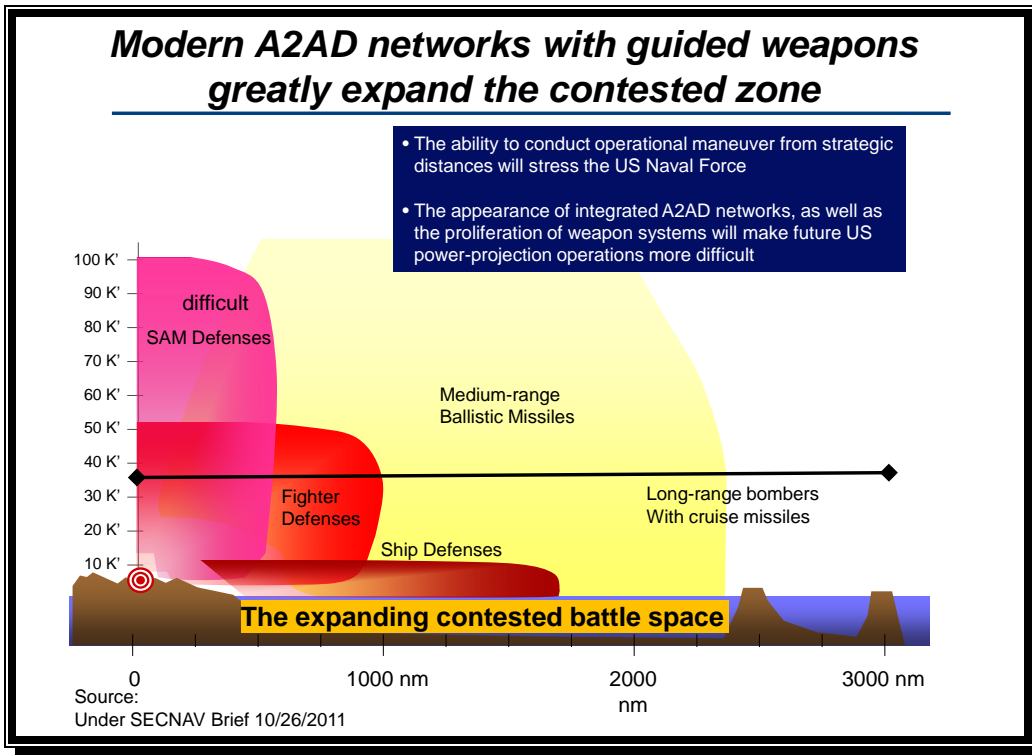
Value of Autonomous Systems

"… the true value of these systems is not to provide a direct human replacement, but rather to extend and complement human capability by providing potentially unlimited persistent capabilities, reducing human exposure to life threatening tasks, and with proper design, reducing the high cognitive load currently placed on operators/supervisors."

Dr. Paul Kaminski
Chairman
Defense Science Board
July 2012

One of the central points of the 2012 Defense Science Board Study is fully reflected in the results of the NRAC panel's research. Autonomous systems do not provide for direct human replacement. Evidence that was gathered through interviews of commercial activity where autonomous systems are in operational use, supports the fact that humans have not been eliminated as a result of autonomy, but rather that the existing manning becomes more effective in doing the job with the addition of autonomous capabilities. In the A2AD mission area, where avoiding human losses and reducing human workload are at a premium, the use of persistent unmanned platforms and intelligent sensors will enable the deployment of highly effective operational architectures.

As the Panel researched the degree to which autonomy may be utilized, it became clear that from a simplified view of the range of decision authority, "full" autonomy is at one extreme of man/machine interactions; automation (i.e., machines doing mostly repetitive work) is at the other end; and, robotic (i.e., un-manned) activity is in the middle. These levels of decision authority are depicted

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in several fashions in this report. But, in the integrated capability environment needed to counter that A2AD threat, some aspects of all three degrees of autonomy would have to be present and rationalized in the same Command and Control (C2) architecture. The degree of human engagement will vary with the degree of decision authority required, but with humans remaining in the loop.

Modern A2AD networks with guided weapons greatly expand the contested zone

- The ability to conduct operational maneuver from strategic distances will stress the US Naval Force
- The appearance of integrated A2AD networks, as well as the proliferation of weapon systems will make future US power-projection operations more difficult

difficult
SAM Defenses

Medium-range
Ballistic Missiles

Fighter
Defenses

Long-range bombers
With cruise missiles

Ship Defenses

The expanding contested battle space

Source:
Under SECNAV Brief 10/26/2011

     Modern A2AD networks will soon present an almost existential challenge to the U.S. Navy's ability to control the world's Sea Lines of Communication (SLOCs). With the non-U.S. proliferation of anti-ship cruise & ballistic missiles, quiet diesel-electric submarines, stealthy sea mines, and other weaponry, competitor and emerging nations will be capable of expanding the battlespace in contested areas – stretching manned platform ISR capability and access beyond its limits. This presents an almost irresolvable problem for the U.S. Navy: a declining order of battle (i.e., number of combatant platforms) with reduced future Defense budgets that limit the number of new starts. Defense planning must mandate a solution that addresses this problem and maintains our capacity to operate in an A2AD environment.

Role of Autonomy in A2AD

- **Unmanned systems required to operate and augment manned Naval capacity (greater numbers), capability**

- **Autonomy is required because of:**
  - Unreliable or contested communications
  - Environmentally driven latency
  - Need for single operator to command, control multiple unmanned platforms
  - High pace and intensity of operations

Autonomous Systems will enable increased platform numbers, reach and capabilities to counter A2AD

The growth of the potentially contested ocean battlespace (especially in the Pacific theater) will make it much more difficult for U.S. Naval forces to project power given the current number of Naval platforms. In a constrained budget environment, the number of aircraft, ships, and submarines is not expected to increase. A particular challenge is amassing the capacity to conduct large-area undersea ISR. Autonomous systems are the only practical means to increase the capacity and capability of the Fleet. However, simply increasing the numbers will not be sufficient. Unmanned platforms provide the opportunity to extend reach and take sailors out of harm's way. However, to relieve the burden on the warfighter, a single operator should be able to command and control multiple vehicles – which typically is not the case today.

Autonomous systems must be capable of operating in denied, degraded, or high latency communications conditions while enabling shortened decision cycles during high intensity operations. The addition of autonomous systems may be the only solution for addressing the evolving strategic A2AD challenge to the Fleet.

There is little doubt about the Navy's stated desire for unmanned systems to enable fleet operations in the near future. The question is how best to get to that state.

There seems to be some disparity, depending on the community, on how unmanned systems should be utilized and what degree of autonomy is the optimal. The desirability of using smart machines to keep humans out of harm's way; to relieve the burden on overloaded analysts; and to extend on-station surveillance reflect commonality among the air, surface and sub-surface communities. Machines are better than humans at tedious, repetitive tasks since they don't get tired or distracted. The challenge is to identify an appropriate and acceptable allocation of tasking between the human and machine. Manning, culture and doctrine are all considerations in determining the allocation. For example, there is no universal view on the degree of autonomous actions to be allowed on armed unmanned systems.

Even the definition of autonomy reflects the biases of the specific development community researchers that are working the various scientific and engineering challenges of fielding working systems. This will be discussed in the next pages.

Matching Naval Autonomy to Mission
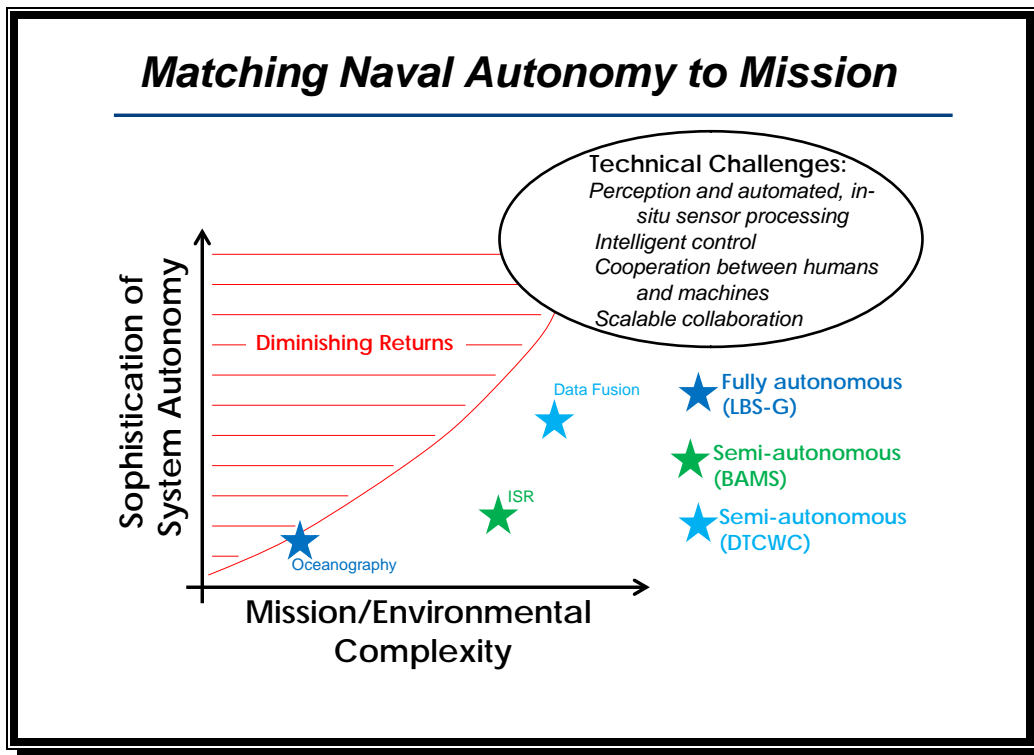
Autonomy is a capability enabled by a variety of technologies, and it does not exist outside the context of a system. There are numerous definitions of autonomy, but one view captures the notion that the system must have some internal ability to resolve choices on its own (i.e., degree of sophistication) in order to achieve goals provided by another entity (i.e., degree of mission/environmental complexity). The decision-making may be simple, reflecting a lower level of autonomy, but all autonomous systems make these choices locally. By contrast, an automated system has negligible ability to make choices - but can follow a potentially complex script - where decisions are made externally. Automated systems may be capable of complex action or operation in dynamic environments, but ultimately the choices are always made by an external operator. Alternatively, as autonomous systems become more sophisticated (e.g., understanding their own limitations and capabilities for a specific mission/environment) – more intelligent operation will result.

It is important for a developer to fully understand the level of sophistication required of the autonomous system for the intended mission and

environment. This prevents costly overdesigned systems – where the increased autonomy capability provides a diminishing return – on the system development cost. For the Navy, ensuring that the system capability is well matched to the mission can improve warfighting efficiency by optimizing the ratio of controllers to platforms. A system need not be sophisticated if the mission application (or deployed environment) is reasonably simple. Some systems can be regarded as fully autonomous even though they may have limited capability. Ocean gliders, operating in a benign undersea environment, are a prime example of this – they are capable of satisfying uncomplicated mission objectives while executing long duration missions – with minimal human intervention. Other systems, operating in more complex environments, would be considered semi-autonomous – even though they are quite sophisticated, for example, BAMS. There are a wide range of capabilities to be enabled with semi-autonomous systems including ISR, data fusion, etc. As the level of the system autonomy decreases, the system is referred to as automated or tele-operated.

The human operator must be considered an integral part of an autonomous system, as the intent is to extend and complement human performance and is not a direct replacement of human function. There are two common relationships that can describe the interaction of the human with the machine. In the first relationship, the human is supported by the machine with human independence decreasing as the functional complexity of the machine increases. In the second relationship, the human provides the support to the machine. In this case, as the machine complexity increases, the number of humans required to support the machine decreases, ideally to zero. When the human is included in the notion of an autonomous system, this helps the designer strike the optimal blend of capability in the machine for the application. For the foreseeable future, there will be numerous applications where the complexity of the decision-making required by the autonomous system will remain beyond the state-of-the-art. For these applications, the system design can leave the decision-making portion with the human, and instead focus on the goal of maximizing the performance of the human-machine collaboration.

Different Views of Autonomy

User View:

Can I give this platform a task, and trust it to accomplish it without constant attention? Can it recognize and deal with unexpected events or ambiguous tasking?

Robotics View:

Can I build a practical robot that does the right thing at the right time? Can I dynamically control, navigate, actuate, and instrument my robot? Can it manage and fuse data?

Machine Learning View:

Can my machine interpret complex sensors? Can it understand spoken language, interpret gestures, or recognize people or objects?

Cognitive View:

Can I make a machine that replicates elements of human intelligence like cognition, inference, and reasoning?

The term "autonomy" carries different implications and meaning within different communities. Developers of robotics, researchers in cognitive science or artificial intelligence (AI), and ultimately the user will tend to approach the question of autonomy from different perspectives. For some, it is a practical design goal, for others it is an area of research closely tied to their particular discipline, and for the user it is a question of functionality. Rather than develop one definition for autonomy, the Panel chose to illuminate the different perspectives, as each has utility within its domain of use.

The user's perspective of autonomy is operationally focused. Their concerns revolve around questions such as: "How will I interact with the robot?" or "How much supervision will be required?" If the answers are that the robot will be difficult to interact with or will require significant supervision, their perspective will be that the level of autonomy is low. If a robot can be easily tasked, and can be trusted to accomplish the task with minimal human supervision, it will be thought to have a higher level of autonomy.

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The technical view of autonomy is far from monolithic. Different research areas define autonomy through the lens of their specific research goals and the class of tools they bring to bear. Researchers who develop entire robotic systems take a comparatively practical perspective, defining autonomy in terms of the nature of the environment and the suite of capabilities the robot can successfully accommodate. In contrast, the AI community is more concerned with how autonomous performance is achieved. The machine-learning community seeks to develop software frameworks using empirical data from existing sensor databases. This ultimately will yield patterns to support a system's self-learning ability to aid human operators.

The bottom-line is that there is no unified view in the approach to autonomy development. Autonomy is an evolving field and it is likely that future systems will be comprised of combinations of these approaches.

Autonomy is widely distributed across the research and application domains. As previously discussed, there are a variety of disciplines contributing to the field, with a variety of concepts and approaches for the development of autonomous systems. These disciplines have diverse models, methods, principles, and underlying assumptions. In some cases, the disciplines do not agree on definitions and "levels" of autonomy.

To achieve optimal results in this field, a coordinated effort will be required. Academic and government research institutions are not organized in such a way to foster the cross-discipline research that is necessary to advance the field. There are limited opportunities for experts in the relevant fields to advertise their work and synthesize their ideas with other researchers. Fostering and providing focus to this community will be critical to advancing the Navy mission. The Panel believes that the most valuable approaches for autonomy research will require multidisciplinary solutions.

There are numerous disciplines that can contribute to autonomous systems. Many of these research areas have received significant funding and have

progressed to the point where they are considered engineering disciplines: navigation, path planning, control system design, image processing, etc. For these fields, the emphasis tends to be on applying the principles to systems, and these areas are generally the constituent components in deployed autonomous systems. There are numerous examples of autonomous systems that are deployed today in a variety of domains that routinely perform these functions. Although more sophisticated algorithms and approaches will improve capability, these functions generally do not limit the capability of current systems or the environments in which they can be deployed.

There is a second category of disciplines that are still in the research phase. These technologies have the potential to greatly improve the capability of autonomous systems, but technical challenges remain before they can be widely adopted into fielded systems. These areas include intelligent control, cognitive architectures, system integration and testing, perception, scalable coordination, and human-machine interaction. Investment in these areas could lead to significant increases in autonomous system capabilities. These technologies in particular are a means to enable capabilities that are unforeseen (or currently impossible) with existing manned systems, but will have lengthy development horizons.

Autonomy Architectures

- **Architectures partition functionality of software components, define component interfaces, and sometimes specify the algorithmic methodologies:**
  - Many organizations have proprietary architectures
  - Open robot architectures include MIT's MOOS-IVP and the Robot Operating System championed by Willow Garage. A consortium has developed MOAA for Naval robotics.
  - Cognitive community approaches include ACT-R (CMU, models human cognition) and Soar (uses include intelligent agents)
  - Hybrid architectures (CARACaS, developed at JPL)
- **Architectures that support portability will allow leverage of rapidly advancing research results.**
- **Interfaces and data ontologies need to be platform independent to support algorithm portability.**

A variety of structured approaches, or architectures, have been developed to provide the software elements of autonomous capability. Architectures partition functionality of software components, define component interfaces, and sometimes specify the algorithmic methodologies. They are motivated by the goals of software reuse, algorithm portability and standardization, and community building. A few example architectures that have been developed for autonomous robotics are described below.

- ACT-R (developed at Carnegie Mellon University) is a cognitive architecture based on a theory for simulating and understanding human cognition. Researchers working on ACT-R try to understand and emulate how people organize knowledge and produce intelligent behavior. The goal is for ACT-R to evolve into a system which can perform the range of human cognitive tasks – capturing the way humans perceive, think about tasks, and act.

- CARACaS (Control Architecture for Robotic Agent Command and Sensing developed at the Jet Propulsion Laboratory) is used for unmanned surface vessel control. CARACaS is a hybrid architecture which includes both reactive and deliberative components.

- MOAA (Maritime Open Architecture Autonomy developed at Draper Labs) is a Government Open-Source Software (GOSS) product developed in accordance with the ASTM F2451 Autonomy & Control Architecture Standard for Unmanned Maritime Vehicles.

- MOOS-IvP (Mission Oriented Operating Suite - Interval Programming developed at MIT) is a set of open source C++ modules with interval programming elements for providing autonomy for robotic platforms, in particular autonomous marine vehicles. The interval programming element of MOOS provides a behavior-based approach to mission-level control.

- ROS (Robot Operating System) is an open architecture effort with its roots in robotics work at Stanford and distributed under the Berkeley Software Distribution license. ROS is most widely used for terrestrial robots and manipulators. The primary goal of the effort is to enable code re-use and achieve portability across platforms.

- Soar (not an acronym) was initially developed at the University of Michigan over 30 years ago and has received support from ONR, DARPA and others. It is "a general cognitive architecture that integrates knowledge-intensive reasoning, reactive execution, hierarchical reasoning, planning, and multiple forms of learning."

Proprietary architectures are not in the best interest of Navy as it endeavors to advance technology and field systems. The diversity of architectures and applications highlights the comparative youth of the field of autonomous control. Researchers are in the early stages of developing component elements. Consequently, one can expect that current systems will increase substantially in performance, and that new approaches will be developed adding unique new capabilities to the "autonomous toolkit."

Architectures that support algorithm portability should be encouraged. The most flexible way to achieve this portability is through developing data ontologies – to enable knowledge sharing and reuse – and to foster common interface definitions that span platforms and the analysis environment.

Examples of Autonomy in the Market

- **Commercial and other government applications exist in all relevant domains but not all development is suitable for Naval use**

Domain	Application	Company / Agency	Technology / Vehicle
Undersea	Oil and Gas	SeeByte	SeeTrack CoPilot
Undersea	Oceanography	Teledyne	Ocean Glider
Surface	Oceanography	Liquid Robotics	Wave Glider
Land	Transportation	Google	Driverless car
Land	Domestic	iRobot	Roomba
Air	Atmospheric Science	NOAA	Global Hawk
Space	Exploration	NASA	Planetary Rovers
Information	Productivity	Apple	SIRI

There is very significant domestic interest in autonomous systems in the government, industry and academia and examples of non-military applications exist in all domains. While many of the autonomous technologies and applications can be leveraged (or outsourced), the Naval Service has unique operational requirements that will require a dedicated and coordinated effort to solve. In general, commercial entities have limited motivation to operate at high speed, operate without detection, deliver ordnance to a target, provide secure communications, operate in a communication-limited (or denied) environment, and sense/operate in the presence of an adversary. Although many of these military-unique challenges do not routinely allow leveraging of commercial or other government investment, many of the autonomous system core technologies have cross-domain applicability.

Today, the capabilities of most systems tend to be in applications where the environment is well defined and/or the mission is of limited scope. In the undersea environment, the applications of current technology generally fit into

ocean sampling and the oil/gas deep sea drilling operations. Unmanned systems used in ocean drilling operations typically enable infrastructure inspection, exploration, mapping, and disaster remediation. These systems have demonstrated significant autonomy (when using mean time between human intervention as the metric), but the application regime of a particular vehicle tends to be narrow. (That is, they do the job they were designed for, but are not easily adaptable to other mission scenarios.)

So far, there is limited commercial interest or development of systems that operate on the sea surface. Although their vehicle capabilities are limited in some aspects (e.g., speed of advance, altitude range), Liquid Robotics, Inc. wave gliders have demonstrated extreme coverage areas and on-station time – requiring only limited human intervention. This particular domain of ocean sampling is thought to be unique to the Navy and so the Navy will have to lead further development activity. Conversely, for the land, air, space and information domains, there are other government and commercial entities with a vested interest in the successful development of autonomous capability. The challenge for the Navy is to identify the set of cross-domain technologies with application to the maritime environment – allowing leveraging of the work of others.

Most of the development in the domestic market, interestingly, is either the direct result of government funding or is a derivative of an initial government investment. This suggests that government seed money can result in significant technical advances, particularly if the problem is carefully chosen to cut across military and commercial applications. Since 2004, DARPA has used the "Grand Challenge" framework to foster significant strides in robotic vehicle behavior benefiting military and commercial interests. If the Navy carefully chooses its technology development projects, some initial efforts can be transitioned to industry for further development – allowing the Navy to focus investment on the technologies and systems that solve Navy-specific problems.

International Landscape

- **US currently leads in Navy-relevant areas, but position is extremely tenuous**
  - Evidence suggests adversaries are very interested in these technologies and are devoting significant resources to close the technology gap
  - US leads in basic research, but in application domain the advantage is less pronounced
    - Manufacturing (worldwide)
    - Human helper robots (Asia)
    - Agricultural applications (Europe)
    - Mining (Australia)
  - Limited-capability applications becoming increasingly inexpensive and easy via COTS products, and open source on-line software. This makes it impossible for DoN to drive the market

The Navy cannot drive the autonomy market. There is a great deal of international interest and research in unmanned and autonomous applications, and the underlying technology will continue to mature and be readily available to our adversaries. Currently, the U.S. S&T effort in autonomy seems to lead the field, but there is more parity in the technology applications. While the focus outside the U.S. appears to be in non-military applications, U.S. peer competitors are expected to devote significant effort to closing the technology gap – and will probably be successful – in the absence of a focused effort on the part of the U.S.

Given the leadership position that our country occupies in the market, one would expect that our adversaries are thinking about countermeasures to our autonomous systems. The Panel is concerned that this poses a future vulnerability to our systems, especially with the knowledge that there so little S&T investment focused on countering their potential countermeasures.

Another concern is that the cost to enter the autonomy market is dropping as Commercial Off-The-Shelf (COTS) systems become more capable and open-source communities become more mature. The general view is that these entry-level systems will have limited capability, particularly with conventional technology, but the capabilities will grow rapidly as the technology matures. Further, tracking international development in autonomy technology is a complicated issue, as large budgets and established infrastructure are not prerequisites for fielding capable systems. This makes it difficult to follow the critical advances, as they can come from smaller, less established entities. It is also noteworthy that some nations lack the ethical and legal restrictions that may constrain the deployment of commercial technologies, which may provide our adversaries more agility in developing and fielding autonomous systems.

Opportunities for Naval Autonomy

- There are potential near-term applications that will provide practical benefit and build trust

  - Ocean monitoring
  - ISR
  - MCM
  - Signature collection
  - Damage control

  - Force protection
  - Infrastructure protection
  - Hull maintenance
  - Logistics

- There are long-term opportunities for autonomy to augment existing forces
  - Capacity to operate in A2AD environment
  - Mine clearing
  - ASW
  - *In situ* ISR data processing to reduce analyst load

Latency, communication, and decision cycle times all drive an autonomous requirement

Early developments in autonomy are being applied to many Naval applications. Various types of Unmanned Air Systems (UASs) using differing levels of autonomy have rapidly expanded beyond the ISR mission, into strike, and force protection missions – greatly reducing the time lag in the sensor-to-shooter chain. Similarly, the role of Unmanned Ground Vehicles (UGVs) has expanded beyond reconnaissance, bomb detonation and disposal, into communications and IED jamming, proving to be a valuable force protection asset in Afghanistan.

As previously noted, Unmanned Underwater Vehicles (UUVs), are being used extensively in the commercial gas and oil industries and for ocean monitoring. They also provide a safe and efficient capability for hull inspection and maintenance. Other Naval applications for autonomous systems include Mine Countermeasures (MCM), acoustic signature collection, shipboard damage control (e.g., fire fighting), force and infrastructure protection, and logistic re-supply to ground troops. As the state of art in autonomy matures, incremental improvements will occur.

To make transformational capability improvements to the very demanding A2AD mission, a focused effort must be pursued to augment existing force capacity (i.e., numbers of deployed platforms) and their capability through the use of autonomous systems in all domains. The challenges for A2AD make the expanded use of autonomy an operational imperative for mine clearing, ASW, *in situ* ISR data-processing, suppression of enemy air defenses, attacking targets, and countering enemy threats including an adversary's autonomous systems. Furthermore, these systems will need to operate in degraded communications environments and at high operational tempo. This will also drive a need for high levels of autonomy.

State of Fielded Systems
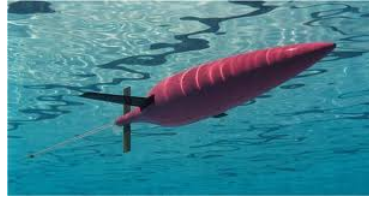
- **Vehicles**
  - Most fielded systems require a high level of human interaction
  - Autonomy most advanced in environments limited by communications (ocean gliders)
- **Information**
  - Current approach is centralized post-processing of data
  - Automated, in situ processing required to deal with explosive growth of ISR data

Today, most fielded unmanned vehicles require a high degree of human interaction. Tele-operated systems, such as early UGVs, required constant external (human) input. Although some UAVs can execute autonomous take-offs and landings and can navigate autonomously, they still require near-constant human supervision during the mission phase for both vehicle and payload. The highest level of autonomy that the Panel observed was in some types of UUVs. Ocean gliders, for example, can be tasked to transit an area and collect oceanographic data without human supervision. This high level of autonomy was driven by the severe limitation on communications in the undersea environment. Fortunately, in the case of ocean gliders, the ratio of human operators to vehicles will soon be as favorable as 1:10 due to the autonomy capability built into each vehicle.

In the information domain, the current approach is to send as much ISR data as possible to a central site for post-processing analysis. This massive amount of data has placed an extreme burden on human analysts. And, there is much more data that could be collected by unmanned ISR vehicles – but is limited by bandwidth and the number of human analysts. New algorithms are required to perform *in situ*, near real-time data analysis to communicate only critical data while autonomously detecting, classifying, and identifying contacts of interest for further target prosecution.

Example Programs

	Air	Ground	Surface	Undersea	Information
ASW			ACTUV (S&T)	PLUS (Fleet Exp.)	
Expeditionary	RQ-7 Shadow **(PoR)**	AEODRS **(PoR)**	UISS **(PoR)**	Knifefish **(PoR)**	
ISR	MQ-4C BAMS **(PoR)**	PackBot **(PoR)**	MUSCL (Fleet Exp.)		DTCWC **(PoR)**
Environmental Monitoring			SHARC	LBS Glider **(PoR)**	
Logistics, Inspection, Test Platforms	AACUS (S&T)		USSV (S&T)	LDUUV (S&T)	

Fundamental autonomy technologies cut across domains

The Navy R&D community has firmly embraced the notion of autonomy and is investing in a multitude of unmanned and autonomous programs in all domains of Naval interest. This chart shows some examples of programs across domains. It isn't meant to be comprehensive but shows that efforts span S&T into Fleet experimentation and programs of record. Brief descriptions of these programs are given in Appendix D. While there are fundamental technologies in the broad realm of autonomy that cut across these domains, e.g., situation awareness, decision-making, C2, health monitoring, interfaces, the Navy must decide whether to continue to pursue the current strategy of near "stove-pipe" development of each program or to follow a more coherent, managed approach within the autonomy domain. The Panel feels very strongly that the latter approach can leverage synergies across these program investments and accelerate the development of autonomy to greatly increase Naval capabilities.

Manual MCM

Program → Navigate/D/C/L → Recover → Analyze/Mine ID
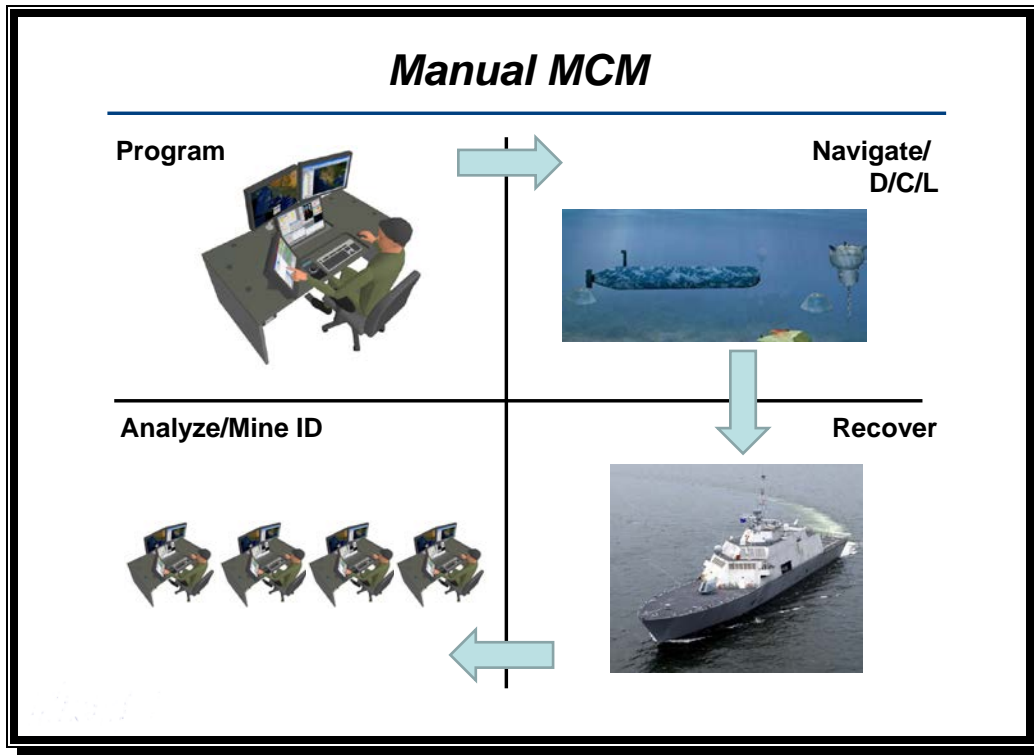
Mine countermeasure operations provide a useful framework from which to explore advances in autonomy. The Knifefish UUV, a Littoral Combat Ship (LCS) payload, maps the seafloor with its low-frequency broadband synthetic aperture sonar and records data from mine-like targets of interest including detection, classification, and localization (D/C/L). The vehicle, with its large data sets, then must return to the ship where human operators can review and evaluate the sensor data to make the final identification of mines (mine ID). The vehicle can be re-tasked without recovery, but the limiting step involves human review of the sonar data set. Follow-on activities might involve further inspection of the identified mine and its neutralization. As shown in the graphic above, the sequential nature of the required activities impose comparatively high transit and navigation requirements (i.e., target acquisition/reacquisition) and an expanded timeline penalty to the Area Clearance Rate Sustained (ACRS).
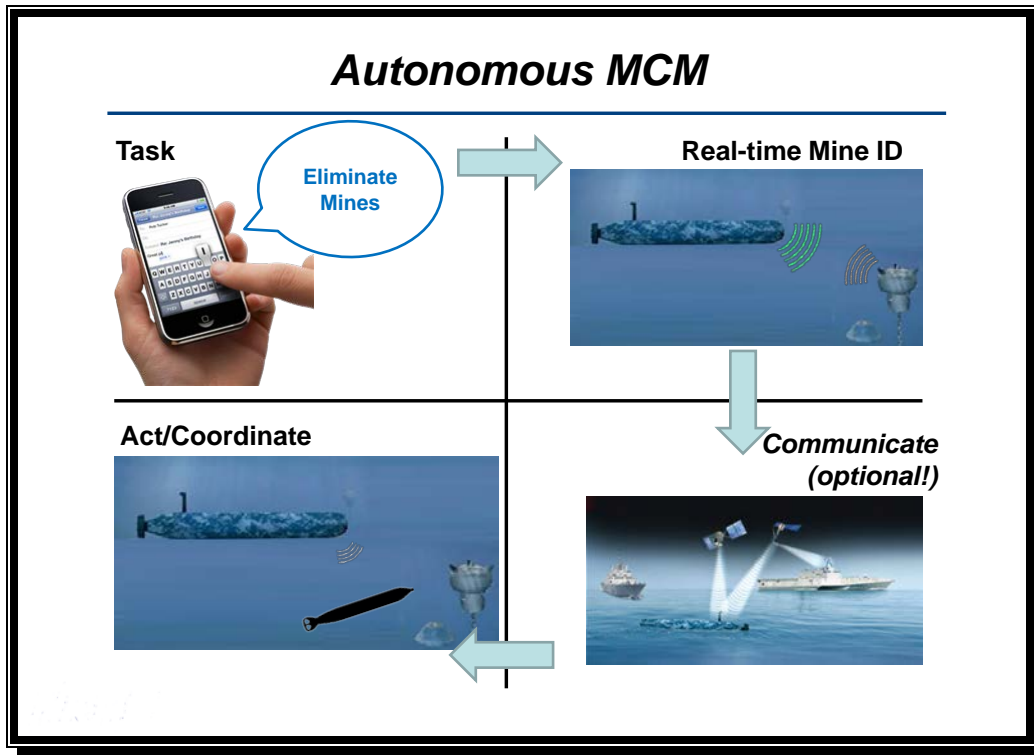
Autonomous MCM

Increasing the autonomous functions aboard the UUV could reap substantial gains in ACRS. Improving sensing and sensor analysis capabilities to the point of definitive mine detection, classification, and identification autonomously, would transform operational opportunities and timelines. With improved autonomy, a trusted system would only need to report high-level information about its mine search process, requiring much less bandwidth for communication with operators and eliminating the need for a mid-mission recovery. UUV collaboration capabilities could enable the Knifefish to interact with a second armed UUV to neutralize mines. If the architecture is scalable, much higher search rates could be achieved with large numbers of mapping and neutralization vehicles working together. Improved onboard decision making could greatly accelerate the tactical timeline and enable MCM to approach an in-stride capability.

> ### *Technical Opportunities*
>
> - **Perception and automated, in-situ sensor processing**
>   - Sensors (miniaturization, power efficiency, sensitivity, cost)
>   - Software for processing and interpretation
> - **Intelligent control**
>   - Independent, mission-focused action
>   - Adaptive behaviors
> - **Cooperation between humans and machines**
>   - Natural interaction (language, gesture, etc.)
>   - Understanding with high levels of abstraction
>   - Interpreting commander's intent
> - **Scalable collaboration**
>   - Collective behaviors
>   - Decentralized control

The Panel noted that there are several technology areas that can offer a good return on investment in future systems.

Autonomous perception and intelligent control are important in allowing the system to deal with uncertainty in a dynamic environment (e.g., changes to system status or mission, adversary countermeasures) and to modify its operations as necessary. Sensor processing that is remote from "home base", becomes a huge force-multiplier when large number of unmanned platforms are in play.

In the area of man-machine cooperation, there should be natural (i.e., intuitive) interaction of the operator with the autonomous system. To achieve this, natural language protocols and gestures can be developed – based on the advances of today's smart phones in language recognition. There are also subtle man-machine interactions – recognizing ambiguities in an operator's tasking or perceiving that an operator is distracted – that need to be resolved before autonomous systems effectively work in partnership with human operators.

The austere communication environment found underwater is one factor that drives the requirement for scalable collaboration by multiple systems to complete a complex operational task. The potential scalability of autonomy offers a technological challenge with significant payoffs: allowing a downsized Navy to operate autonomous machines with sensors to conduct surveillance in large volumes of ocean – and to analyze and act on the processed information.

Collaboration among autonomous systems enables more mission complexity and in-stride operations, as described in the MCM example. The ability to collaborate also offers scalability of systems through efficient resource management and task-sharing across systems.

Trusting Autonomous Systems

- Systems with a high degree of autonomy <u>will be different</u> from legacy systems
    - Interaction with human supervisor
    - Not rule-based
    - Systems will perceive and understand the environment and reason (e.g., new anti-torpedo torpedo)
    - Self-supervised learning
    - Multiple coordinated systems – i.e., swarms

- Challenge – How to test these systems to establish trust?

In this text and in the text that follows, "testing" and "experimentation" will be used interchangeably. In the future, both may be used to designate different parts of an overall trust-building process, however. "Experiment" could eventually describe the detailed hypotheses to be examined; "tests" may describe the actual operations and measurements to validate the hypotheses.

Building trust with the human supervisor encompasses the ability of autonomous systems to work as trusted, collaborative partners with humans. This state of trust is probably the single most important aspect of the proposed transformation in Naval Operations. By their very nature, future unmanned systems with high levels of autonomy will be substantially different than today's legacy unmanned systems – which are primarily rule-based systems which require specific commands and decisions by human operators with specific rules for implementation.

In the future, a key system difference will be a system's ability to naturally interact with the human supervisor, to understand his or her operational intent, to use stored or *in situ* measurements to perceive and understand the actual

environment, and to consider and execute alternative courses of action. Autonomous systems will be self-governing, based on constraints provided by the human supervisor and will be capable of collaborating with other autonomous systems without significant external input. Clearly, this level of autonomous intelligence and learning capability will require substantial testing to establish the requisite human trust for the selected mission. The testing must be iterative – with the machine and the human working together to establish increasing levels of demonstrated learning, with important operational and physical environments included in the experiments – and, with all of the required testing metrics.

The introduction of higher-level autonomy into unmanned systems will present new technical and management challenges. It requires a shift from testing system specifications to testing systems like we test humans. This test approach will require a well-focused R&D activity to establish and validate new experimental protocols and to develop and build whatever unique testing facilities are required.

Testing Autonomous Systems

- Testing must:
  - Build the trust required for effective operational employment
  - Verify system meets legal and ethical requirements and is accepted by military and civilian communities
- Trust-based testing protocols need to be developed:
  - Require capable facilities
  - Simulation plus actual field testing
  - Safety as well as proving mission competence is essential (e.g., optionally operated systems)

A trust-based testing philosophy requires an extension of current testing techniques

In addition to the traditional testing regime that examines expected system capability and performance, the testing of autonomous systems must carefully verify that each meets legal and ethical requirements and that the system is accepted by both military and civilian communities, as necessary.

In order to develop and test the required protocols, capable data gathering facilities and realistic, data driven, simulations are required to verify that the autonomous system software will operate as expected in a possibly highly dynamic environment. For example, facilities may require multiple platform tracking and C2 capabilities, or may need to replicate multiple environments to comprehensively test system perception. The protocols will need to ensure the safety of the testers and equipment in addition to demonstrating mission competence. For example, systems in development may require selectable modes of operation that initially permit 100% human control but scaling to only limited external supervision as trust in the system is demonstrated.

It is expected that the operator/tester community for autonomous systems will require a new set of skills that are not required for testing legacy equipment. Trust-based testing will represent a significant extension of current testing techniques.

Value Added from Testing

- Trust-based testing will constantly evolve as operator gains confidence in the system and the system performance improves

- This testing results in transferable, validated algorithms which are exercised against and "tuned" to real world data for implementation in system

- These trusted algorithms and the accumulated data become the "secret sauce" that will provide the US its technological edge

It is a given that the development and implementation of trust-based testing will require the investment of scare resources. It is useful then to discuss the potential added value of such testing. First, the upper limits of capability enhancement that this kind of testing can produce have not been established. What is clear is that trust-based testing is an evolving process. Each step will build on the past with no clear bounds yet established allowing both the "operator and the autonomous system to gain confidence in working with each other". Second, the testing output (e.g., validated, transferable algorithms) is "tuned" to real-world data for subsequent software upgrades to the system.

This combination of evolving algorithms and large data sets are two items that should survive the worldwide commoditization of many of the supporting (and ubiquitous) technologies – providing U.S. forces with continuing technological superiority – not easily overcome by an adversary.

Autonomous Systems
Lifecycle Support Chain

- Need early development of doctrine and CONOPS and coherent articulation of fleet support mechanisms

- Challenge in Fleet introduction of autonomous systems includes
  - Ensuring adequate manning
  - Developing and executing a robust logistics management plan
  - Executing DOTMLPF responsibilities in a manner that reflects manning plans and logistics support

Introduction of autonomy as a capability potentially impacts all aspects on Naval operations. In this regard, lessons learned from implementation of disruptive technologies are instructive. The literature and experience points to the difficulty of most large organizations in adroitly assimilating disruptive technology. The latest DoD example is the experience with UAVs. Despite their demonstrated wartime value, the Department is still struggling with doctrinal, manning, basing, and training issues, aside from the fundamental acquisition tensions.

The difficulties in technology assimilation are understandable, particularly in enterprises that must give heavy emphasis to minimizing risk to operations. Risk avoidance drives the need to have technologies introduced with great transparency to the user community, especially when considering doctrine,

implementation and support. The enterprise must be assured that all aspects of the introduction of new technology have been considered.

The need for transparency and balance cannot be readily satisfied with the current structure and processes. Disruptive technology is unpredictable, so studies have focused on identifying characteristics that allow an organization to incorporate disruptive technologies into their product line. It has been asserted that many organizations fail to meet the challenge posed by introducing disruptive technologies because the focus is primarily on resources, rather than processes and values. This would seem to apply to DoD for some new system roll-outs. Processes include the coordination, communication, decision-making, and interaction patterns that transform resources into products. An organization's values frame how priorities are set and also how success is defined. The Panel believes that having a central focus for this "product" introduction is essential to achieving success in enabling successful assimilation. The current multiplicity of efforts in pursuing autonomy-related technologies is a prime example of the impact of lack of central focus.

One obvious area of a new system's implementation – requiring Fleet acceptance – is adequate warning of changes to manning requirements. The U.S. Air Force was initially unprepared for the large cadre of personnel required for Predator squadrons in a wartime environment. Accordingly, comprehensive manning and support plans that are developed before deployment will provide a transparent mechanism to encourage assimilation. Also, adequate maintenance and spare parts plans must be realistic. If operators do not have confidence that a system can be relied upon over the duration of a deployment, they will be reluctant to rely on the new technology for accomplishing mission objectives.

Careful consideration for transparent Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel and Facilities (DOTMLPF) principles will help to reassure the Fleet in adopting autonomous systems.

Legal and Ethical Issues

- Legal and ethical considerations will effect system design and CONOPS development
- Implications in an operational context require early Navy leadership
- No universal definition of the status of "autonomous systems" exists
    - There are consequences to the definition
    - Autonomous ships/vessels, UAVs, and weapons (e.g., CAPTOR) are in different states of definition
    - Size and degree of automation are factors
    - Immunity and salvage rules governed by international acceptance of definitions
- Greater emphasis must be given to ethical issues early – a departure from historic practice
- Using legal/ethical benchmarks in the technology development process protects against capital investment missteps

Indeterminate status of answers to issues involved suggests the need for more focused attention

As the Panel investigated a range of issues underlying Fleet acceptance of unmanned systems, the evolving ethical and legal considerations emerged as critical areas to be addressed that will affect future design and CONOPS. We see these issues playing out now over the increased utilization of UAV systems for military strike missions as well as their potential domestic use in U.S. airspace.

Legal and ethical issues can play a large role in the successful or unsuccessful implementation of a new capability. There is ample evidence of the Navy being unable or unwilling to fully investigate the environmental impact of low-frequency active sonar operations. Starting in the mid 1990s, the Navy was placed in legal jeopardy – negatively impacting the development and testing of these critical systems. The Panel concluded that the military establishment must consider ethical issues early in the development process. There is some good news, however, an NPS-sponsored a Roboethics Symposium for the Warfighter held in 2012 and the Secretary of the Navy sponsorship of a future workshop to examine issues revolving around "due care" testing.

From the purely legal perspective, the Panel found that there is a large void in the definition and status of military autonomous systems in the international arena. This means that all of the underwater, surface, aerial vehicles and weapons (e.g., CAPTOR-like capability) – with their variety of size, use, deployment method – will eventually have their legal status determined based on their degree of autonomy and other factors. This legal status should inform development and testing and determine immunity and salvage rights that are accepted by the international community. Careful tracking of international discussions in this area is important.

As previously discussed, the commercial sector has begun to operationalize autonomous systems in the oil and gas exploration industry. Legal status, including definitions and standards, is being established for insurability considerations, and defining liability of manufacturing contractors for system performance. These legal considerations will also apply to Naval systems.

The Panel believes that Navy leadership should be actively engaged in the oversight of the evolving ethical and legal discussions that will shape future systems.

Safety and Security

Safety
- UAS operations
  - UAS operation in civilian airspace
    - Current inability to comply with FAA sense and avoid rules without ground observer or chase aircraft
    - Challenges: UAS C3 and sense and avoid
    - Cultural acceptance of mixed use of airspace
- USV and UUV operations
  - Collision regulations at sea (COLREGS)
  - Discussions began this year on regs for USVs and UUVs
  - Today small unmanned systems considered debris

Security
- Protection from deception and loss of comms
- Protection of the asset
- Protection of the technology

The absence of comprehensive Federal Aviation Administration (FAA) regulations governing Unmanned Aircraft System (UAS) operation in civilian airspace continues to be a significant hindrance to the expansion of the UAS market. Despite this, many government agencies are operating UAS vehicles: the departments of Defense, Home Security, Justice, as well as the Federal Bureau of Investigation, National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, state and local agencies and qualifying universities. Currently no UAS has demonstrated to the FAA that there is a reliable method to comply with "sense and avoid" rule without having either a ground observer or chase aircraft acting as the "eyes" of the UAS. Specific FAA authorization is required to operate a UAS in the unrestricted national airspace system. The FAA views the sense and avoid requirement as critical but has missed several deadlines for providing industry the guidance needed to meet the requirement.

The challenges that need to be overcome to enable large-scale operation in the national airspace system are the development of an FAA-certifiable sense and avoid capability plus the communication, command and control systems (C3) to enable FAA to fold UAS operations into controlled airspace. Another problem is the potential for spoofing of GPS signals or uplink/downlink UAS commands. Even after these challenges are solved and accepted by the FAA, cultural acceptance by the "manned" aircraft community for mixed operation of unmanned and manned systems will need to be achieved. (On a positive note the Aircraft Owners and Pilots Association has put out material to educate pilots on the need for integrated airspace for UAS and manned aircraft and how UAS operations are managed and flown today to ensure safety.)

Although the operation of USVs and UUVs has not reached the level of safety concern as UASs, primarily because their numbers are not yet as large, the challenges may even be greater to overcome for compliance with the Collision Regulations at Sea (COLREGS) and the Law of the Sea (LOS). Discussions began this year on the development of regulations for the safe operation of USVs and UUVs, and ONR has been working on incorporating COLREGS-compliant high-speed collision avoidance features. An interesting LOS sovereignty interpretation is that a small UUV that surfaces to communicate, while dead in the water, can be considered salvage, and many be "rescued" by passing commercial vessels.

As noted, the protection of the unmanned system from deception (e.g., spoofing, redirecting, shutting down, etc.) or from stray electromagnetic emissions must be developed and proven to ensure security and safety. Regardless of the degree of autonomy, unmanned system will need an ability to communicate for re-tasking, sending back critical information, updating targeting from ISR sensors, etc. Communications assurance will need to be developed and proven to the level needed to achieve system trust.

Finally, the platform itself – as well as the information it collects, transmits or stores – will need to be protected using advanced anti-tamper techniques to prevent access to the data and the underlying technology.

As previously discussed, operator trust is central to any successful assimilation of disruptive technology. A harmonized integration of the various elements (e.g., doctrine, CONOPS, testing, training, manning, legal and ethical considerations) during the introduction of new technology can produce a broadly-based understanding of the scope, interrelationships and paths to successful Fleet introduction. It will significantly increase the operator's willingness to accept the risk associated with the use of the new technology.

Given the disruptive nature of autonomous technologies, Fleet participation has value in developing realism and also providing familiarity with the capability. This acceptance by the operational community should occur before the system reaches its Initial Operational Capability.

Finally the Panel recognized, as we spoke with various subject matter experts, that traditional weapons system testing constructs would be challenged in

ways that would only be discovered as autonomous systems evolved. There was general agreement with the proposition that the testing of autonomous systems will be similar to the way humans are tested – in that the ability to complete a task in varying conditions – was of key importance.

Findings:
- With the expansion of the contested fleet operational zone, autonomy is the best opportunity to transform Naval Operation by enhancing capacity.
- The widely distributed state of the technology, breadth of applications and diversity of expectations make fielding autonomy a complex challenge
- Previous examples of Naval transformation demonstrate that community orientation and senior leadership are required for success

Recommendation:
Establish an Autonomy Community – led by a senior champion – composed of technical, acquisition, requirements, and operational experts to <u>focus</u> on autonomy for Naval needs **(Action: SECNAV/CNO)**

The A2AD challenge to the U.S. Navy is well documented – especially when fewer platforms and reduced year-to-year Total Obligation Authority (TOA) are considered. Autonomous systems, working in collaboration with legacy platforms and capability, can provide the increased capacity and capability to meet this challenge.

By its very nature, transformational technology introduction is difficult, especially when the strategic and tactical performance of an organization affects national priorities. It can only be accomplished with strong leadership, and a well-defined community of interest. There are a number of examples of significant Naval transformation led by a senior champion and a focused community. The introduction of Naval Aviation was enabled by the creation of the Bureau of Aviation under Captain Washington Chambers in 1913. The transformation to a nuclear Navy was led by Captain (later Admiral) Hyman Rickover in the Naval Reactors Branch. The implementation of the Naval portion of the Triad (of

strategic deterrence) was accomplished through the establishment of the Special Projects Office (1955) under Rear Admiral William Raborn.

Therefore, the Panel recommends that an Autonomy Community be established and led by a senior champion or advocate to begin to transform our Navy.

Building an Autonomy Community

Technology and Operational Communities

Naval S&T Community, DARPA & Other DoD Components, NWDC, Academia, US & Global Autonomy R&D

Requirements Community

Fleet and Domain Enterprises

Programmatic Community

Navy PMOs, Other Government PMOs, Defense & Commercial Industry

Focus and Advocacy

Special Projects Office

Increased Levels of Integration

Focused Autonomy Technology Resources

An Autonomy Community is required to align government needs & efforts with commercial advances

The level of autonomous system implementation will only be raised by intentional focus on autonomy as an overarching capability. An autonomy community, led by a senior advocate is essential to bring about this focus. This *Naval Autonomy Community* will facilitate strong cross-domain interaction – bringing technologists and Fleet operators together to identify Naval needs and work common technical challenges. The community will be able to identify synergies within and across domains and work to eliminate barriers to delivering autonomous systems to the Fleet.

A Naval Autonomy "Specials Projects Office" with full authority to guide the autonomy community would be responsible for providing focused allocation of resource investments of all autonomy S&T and R&D programs that respond to Fleet & OPNAV capability requirements and program managers' technical requests.

Additionally, this senior autonomy community advocate would also work closely with OPNAV and Fleet Commanders to develop strategy and execution roadmaps to integrate and implement autonomy technologies into programs of record that enhance the capabilities and capacities of current and future fleet systems. The Special Program Office lead by the Naval Autonomy Advocate would specifically control all interface technical specifications associated with autonomy systems and subsystems.

The Panel found ample evidence that the autonomy domain is still significantly driven by technology "push". In order to create requirements "pull" and to ensure user adoption of autonomous systems, it is critical to build user trust. Trust-building begins in the design and development phases by requiring Fleet involvement throughout the development process – not just during the final stages of experimentation. The Naval autonomy community advocate will be responsible to ensure early and sustained engagement by all communities throughout the system development, testing, and deployment stages.

Potential S&T Process to Support Naval Autonomy Development
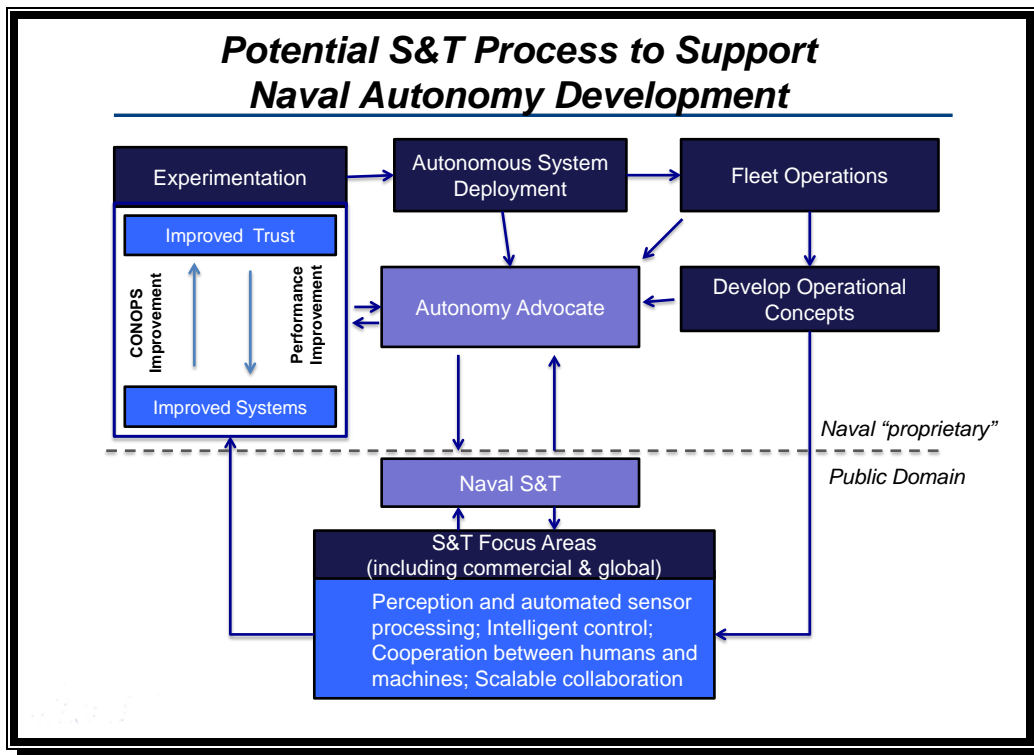
The development and maturation of any operationally-oriented technology typically requires several cycles of conceptualization, technology development, experimentation, deployment (of prototypes) and use by the operators to realize full potential. This cycle is shown around the perimeter of the graphic above.

One should note that there is a "meta-cycle" within the experimentation process which is unique to the operational employment of autonomous systems, because of the importance, discussed extensively elsewhere in this report, of trust in the autonomy technology. The operational employment of autonomous systems will require significant trust to be established, via trust-based testing and experimentation, in order to reap the potential benefits of this emergent technology. Further, only through experimentation will it be possible to enhance the performance of autonomous systems, perhaps by constraining their "freedom" as the limitations of autonomy algorithms are discovered in experimentation.

However, the technology development needed to offer transformative capability to Naval forces in the area of autonomy bring special complications resulting from both the operational scenarios in which autonomous systems may be used, and from the field of suppliers and developers of relevant technology.

As noted previously, potential near-term opportunities for autonomous systems to play important roles include highly sensitive applications in ISR, signature collection, and force protection. On the other hand, much of the relevant technology of autonomy is not developed within the DoD, or by DoD contractors, and increasingly includes international suppliers. Thus, rapid insertion of autonomous systems requires special handling to define the technology challenges to be provided to technology developers. But, even identifying relevant technology from the full panoply of potential suppliers is difficult, without revealing sensitive details of the target mission and operations.

The Panel suggests that these difficulties can be addressed with a very small group that reports to the Naval Autonomy Advocate discussed in the first recommendation. The small group should have a representative from the Fleet, Special Programs, and ONR. They should be cleared into to all relevant programs where autonomous systems could be used; they would then be in a position to guide Naval S&T investment to develop technology that would enable rapid insertion of autonomy into operational contexts, without exposing the operational scenarios more broadly in ONR and the technology development community. Variants of this approach have been used successfully by the DON, for example in the contexts of low-observable technology and certain areas in undersea warfare.

This approach will significantly enhance the opportunities for autonomous systems to be rapidly inserted, with potentially transformative effect.

Findings and Recommendations (2)

Findings:

- There is an interrelationship between Naval opportunities for autonomy with commercial and other government applications

- Given the widely distributed developments ongoing, there is a need for a systematic examination of autonomy technology developments both domestic and international

Recommendation:

Periodically commission an outside market survey to access, analyze and assess global autonomy markets that may be relevant to its efforts **(Action: CNR**)

In the current environment, technology development is a global enterprise. In the past, the U.S. was able to develop, apply, and control selected technologies related to space, weapons systems, communications, computer hardware and software, and others. Today, most technology development and insertion is done for commercial purposes – much of it is done outside the U.S. This is true even for autonomy technologies.

The Panel recommends that ONR, on a regular basis, commission a market survey of the autonomy market and technologies to ensure that Naval S&T is cognizant of autonomy technology advancements outside the U.S.

Given the need to introduce autonomous systems into the Fleet, careful consideration and focus must be given to the implementation and adequate resourcing of autonomy technology areas. Stove-pipe approaches with erratic year-to-year funding lines cannot provide the path for a successful transformation.

The Panel recommends that senior Naval leadership take the responsibility to assure adequate overall autonomous system funding; and assure focus in these key enabling technology areas: automated, in-situ sensor processing; intelligent control; cooperation between humans and machines; and scalable collaboration.

Findings and Recommendations (4)

Finding:
- To build trust, autonomous systems must appropriately reflect a range of issues such as legal, ethical, safety and security considerations
- Testing is central to achieving operational user acceptance.
- Autonomous systems differ from legacy systems and require new test methodologies as well as adequate facilities

Recommendations:
Develop protocols and enhance facilities as necessary to support autonomous systems testing and "trust building" **(Action: CNO N84)**

During the fact-finding portion of the study, it became obvious to the Panel that full acceptance of unmanned autonomous systems by the operational Navy would require a high degree of trust in deployable systems. A commanding officer must be assured that the system that he or she operates (usually away from the ship) will safely and effectively execute its mission. Building trust in autonomous systems must appropriately reflect a range of issues such as legal, ethical, safety and security considerations – with a testing regime that require new protocols and methodologies not used test and evaluation processes for today's legacy systems.

The Panel recommends that the Naval establishment develop protocols and enhance facilities as necessary to support autonomous systems testing and "trust building".

Take Aways

- **Autonomous Systems represent a transformational capability for Naval Operations in all domains**

- **A sense of urgency is required to create a focused, cross-domain Naval Autonomy Community**

- **Continuous experimentation with the fleet will be essential in generating and maintaining the trust that will be required**

- **Validated algorithms and data generated by these experiments will provide DoN with a sustaining technological and operational advantage.**

The Panel strongly believes that autonomous systems technology is advancing rapidly and has reached the potential to enable a truly transformational capability for the Fleet today – especially the A2AD Naval challenge in anti-submarine warfare, suppression of air defenses, and mine countermeasures. There are several top-level take-ways from the study.

The first is that a focused Naval Autonomy Community must be created which builds on the diverse set of technical, operational and policy experts already working in this field to focus on specific Naval missions. To accomplish this, the Panel believes that strong Naval leadership will indicate a sense of urgency in critical mission areas.

The second is to build user trust in operating autonomous systems with comprehensive Fleet experimentation – providing validation of system algorithms and data sets. It also requires a strong R&D commitment with emphasis on lifecycle support issues, legal and ethics considerations. User trust is absolutely essential for this new capability to realize its full potential in sustaining a technological and operational advantage for the Fleet.

Appendix A: Panel Biographies

(Panel Chair) Chair – Dr. Patricia L. Gruber is the Deputy Director of the Applied Research Laboratory (ARL) at the Pennsylvania State University with responsibility for strategic planning, overall direction of laboratory and accountability for 1,200 faculty, staff and students (2009 – present). Dr. Gruber served as the Director of Research at the Office of Naval Research where she was responsible for Naval S&T strategic planning and for the overall integration of the Discovery and Invention portfolio (6.1 and early 6.2) in support of naval mission areas (2006-2008). Prior to her ONR assignment, she served as a Senior Research Associate, at ARL Penn State, focused on opportunities to expand ARL research funding base and build core capabilities in defense technologies (2003-2005). Dr. Gruber has held a number of technical management and business development positions at Lucent Technologies Bell Laboratories and Marconi Communications focused on successful delivery of telecommunications networks (1996-2002). At AT&T Solutions, she was a solution architect responsible for development and implementation of complex IT outsourcing contracts. As a Distinguished Member of Technical Staff at AT&T Bell Laboratories, she was a program manager for Navy undersea surveillance programs. She began her career as a Research Physicist in the Acoustics Division at the Naval Research Laboratory. Dr. Gruber is a recipient of the Superior Public Service Award. She is a member of the Army Science Board and the Acoustical Society of America. Dr. Gruber received a BS in Meteorology from Penn State and a MS and PhD in Marine Physics from the University of Miami.

Vice-Chair – Rear Admiral Charles Young, U. S. Navy (Retired) was previously the Vice President for Strategic Business Planning, Oceaneering Advanced Technologies. Admiral Young served on the *USS ULYSSES S. GRANT* (SSBN 631B); *USS PLUNGER* (SSN 595); *USS SAND LANCE* (SSN 660); USS *SAN JUAN* (SSN 751) and *USS HOLLAND* (AS 32). Shore duty assignments included instructor duty at Nuclear Power School, Bainbridge, Maryland; Squadron Material Officer on the staff of Commander Submarine Squadron Sixteen in Kings Bay, Ga.; Director of Tactical Training at the Navy Fleet Ballistic Missile Submarine Training Center in Charleston, S.C.; Deputy Commander for Readiness and Training for Submarine Squadron TWO and Undersea Warfare Assistant Office Director for Advanced Submarine Technology in the Defense Advanced Research Projects Agency. Additionally, he served as Director, Resources and Evaluation on the staff of the Assistant Secretary of the Navy for Research, Development and Acquisition; Program Manager for the Navy's Unmanned Undersea Vehicles Program Office; Deputy Commander,

Naval Sea Systems Command for Undersea Technology; Commander, Naval Undersea Warfare Center; Vice Commander, Naval Sea Systems Command; and Program Executive Officer for Undersea Warfare, Rear Admiral Young was the 11th Director of Strategic Systems Programs where he was responsible for all aspects of the research, development, production, logistics, storage, repair, and operational support of the Navy's Fleet Ballistic Missile Weapon Systems. Since retirement from the Navy, Admiral Young has served on several panels and boards. These include: Submarine Superiority Technical Advisory Group (SSTAG), Defense Science Board Task Force on the National Security Industrial Base for the 21st Century; Navy Research and Advisory Committee (NRAC); advisor to the Threat Reduction Advisory Committee (TRAC) Nuclear Deterrent Transformation (NDT) Panel; Board of Advisors for Florida Atlantic University's Institute for Ocean and Systems Engineering; Board Advisors for Johns Hopkins University Applied Physics Laboratory' Global Engagement Department; Board of Advisors for the Navy Submarine League; Board of Advisors for the NDIA Undersea Warfare Division; Board of Directors for the United Services Benefits Association; and Board of Advisors for the Advanced Technology Institute in Charleston, SC.

Dr. James Bellingham is Chief Technologist at the Monterey Bay Aquarium Research Institute, and was Director of Engineering from 1999 to 2006. In his time at MBARI he has elevated its Engineering Department to international stature and established it as a center for advanced ocean observing system technology development. Prior to joining MBARI, Dr. Bellingham founded the Autonomous Underwater Vehicle Laboratory at MIT, running it from 1988 to 2000.   In 1997, he co-founded Bluefin Robotics Corporation, a leading manufacturer of Autonomous Underwater Vehicles, and served on its board until its purchase in 2005. He serves on a number of advisory boards and councils, including Strategic Advisory Group for Battelle's National Security Division. Today Dr. Bellingham is developing a new generation of ocean observation systems tailored to the needs of global climate and ocean ecosystem studies.

Vice Admiral William Bowes, U. S. Navy (Retired) is currently an aerospace consultant, serves on a number of boards and is vice chairman of the NRAC. He served 33 years in the Navy in numerous operational and acquisition assignments. As a Vice Admiral he served as the Commander of the Naval Air Systems Command, the Principal Deputy Assistant Secretary of the Navy for Research, Development and Acquisition (RDA), and for six months was the Acting ASN (RDA). He is an accomplished test pilot, program manager and PEO. He served as the program manager for the F-14 and Phoenix missile program, the Joint Cruise Missiles Project, which developed and deployed the Tomahawk cruise missile, and was the first director of DOD's Joint Unmanned Aerial Vehicles

Project. After retiring from the Navy, Bowes joined Hughes Aircraft as a Senior Vice President and Deputy General Manager of the newly forming Sensors and Communications Sector. After Hughes was acquired by Raytheon, Bowes joined Litton Industries as the Vice President, Corporate Strategic Planning, and subsequently led the creation of the Military Aircraft Electronics Systems business unit after Litton was acquired by Northrop Grumman.

Dr. Fernando Fernandez is a private consultant and a Director for various companies. From 2001-2006 Dr. Fernandez was a Distinguished Research Professor in Systems Engineering and Technology Management at Stevens of Technology. In addition, he served as the Chief Technical Advisor to the President for Institute research initiatives, management of intellectual property and commercialization of technology. From 1998-2001, Dr. Fernandez was the Director of the Defense Advanced Research Projects Agency. Under his leadership, DARPA served as the Department of Defense's premier R&D institution, trailblazing paths in biological warfare defense, information security, precision strike and robotics. Before that he started and managed several successful R & D companies specializing in remote detection and identification of hidden objects. In 2001, he was awarded the Distinguished Public Service Award by the Secretary of Defense and an Honorary Doctor of Engineering degree by Stevens Institute of Technology. Dr. Fernandez received his Bachelor of Science in mechanical engineering and Master of Science in applied mechanics from Stevens Institute of Technology in 1960-1961. He received his Ph.D. in aeronautics from the California Institute of Technology in 1969.

Mr. Charles Nemfakos is a Senior Fellow at RAND after leading Nemfakos Partners LLC in supporting public and private sector clients, here and abroad, in dealing with the demands of the emerging defense/security realities and the pressures of the global marketplace. Previously, Mr. Nemfakos was an executive with Lockheed Martin Corporation, directing efforts to rationalize product lines, providing program focus to enhance competitive strategies, seeking new directions and opportunities for growth among the various Corporation companies by anticipating demands of transformational processes. Mr. Nemfakos served in assignments as a budget analyst and as a planner in the Office of the Secretary of Defense and the Department of the Navy. He served in a variety of financial positions, as Deputy Assistant Secretary for Installations and Logistics, as Deputy Under Secretary, and as Comptroller. He was responsible for formulation, presentation, and execution of the Department's budget, directing the base closure process, providing executive-level continuity in institutional management and strategic planning, and supporting privatization initiatives, incentive structures, and right-sizing efforts. Mr. Nemfakos was the Department's Chief Financial Officer. He played a central role in the transformation of the Department after the

Cold War. Mr. Nemfakos has lectured extensively on public policy in resource allocation, on national security issues, on public administration policy and on public/private entity relationships. He has served on Boards of Directors and/or Advisors of companies and non-profit, educational entities, as a Senior Fellow at the Center for Naval Analyses and an Adjunct at the National Defense University. Mr. Nemfakos has been recognized by three U. S. Presidents with four Presidential Rank Awards, by the Secretary of Defense as one of nine Career Civilian Exemplars by American University with the Roger W. Jones Award for Executive Leadership, and by National Academy of Public Administration as an elected Fellow.

Mr. Daniel O'Shaughnessy is an engineering professional with many years of experience in guidance and control, mission design, navigation, aerodynamics, and spacecraft operations for atmospheric and exo-atmospheric flight. He is currently the Autonomous Aero-breaking Lead Engineer for the Mission Design, Guidance and Control Group, Space Department at the Johns Hopkins University Applied Physics Laboratory. In his capacity as Lead Engineer, he directs research in the development of 6-DOF simulations for autonomous aero-braking demonstration. He is also the MESSENGER Guidance and Control Lead Engineer where he planned, designed and implemented orbital insertion maneuver, marking the first robotic spacecraft into orbit about Mercury. His experiences include managing teams of senior engineers and mentoring junior staff members. Mr. O'Shaughnessy holds a BS and a MS in Mechanical and Aerospace engineering from the University of Missouri-Columbia where he graduated cum laude with honors. Mr. O'Shaughnessy has authored and co-authored numerous publications regarding the MESSENGER spacecraft.

Dr. John C. Sommerer is Head of the Space Sector at Johns Hopkins University Applied Physics Laboratory (APL), which is the largest of the DOD-affiliated University Research Centers. He is responsible for all APL activity in support of NASA and DoD, including seven currently operating missions, four missions under development, over a dozen instruments, and over 150 current science investigations. He has served at an executive level at APL since 1996, including 10 years as Chief Technology Officer. In 2011, he was elected to the International Academy of Astronautics, and was named an Inaugural Daniel Coit Gilman Scholar, designating him as one of the foremost thought leaders at Johns Hopkins University. He is an adjunct faculty member in several programs of the G.W.C. Whiting School of Engineering at Johns Hopkins University. Dr. Sommerer also serves on multiple technical advisory bodies for the U.S. Government and is a National Associate of the National Research Council.

Appendix B: Terms of Reference

How Autonomy Can Transform Naval Operations

Objective

This study by the Naval Research Advisory Committee (NRAC) will endeavor to clarify the potential of autonomy to transform naval operations. The study will explore the current and anticipated potential of technology to achieve various levels of autonomous operations. The study will also consider potential naval uses of autonomy, with emphasis on maritime systems, and the challenges associated with realization of these applications.

Background

The growing demand for naval forces and an increasingly constrained fiscal environment require hard choices today - and will require the Navy to evolve and innovate for the future.

The most concerning area for naval capability development is the fielding of A2/AD capabilities by nations and non-state groups. These capabilities include mines, submarines, anti-ship cruise and ballistic missiles, anti-satellite weapons, and communications jamming. These weapons are designed to support aggression and coercion against neighbors while preventing intervention by U.S. or allied forces. The Navy is investing in research and development efforts and procurement programs to overcome these threats to access, and assure the ability of the Joint force to project power in support of our allies and partners and protect U.S. interests.

An important element of overcoming threats to access and maximizing the fleet's capacity is unmanned systems. As a result, autonomy and unmanned systems have been identified by Naval and DoD leadership as a high priority. However, specific pathways for the introduction of technologies that enable greater levels of autonomy have not been identified.

Scope

The study will consider autonomy as a capability which is enabled by a set of technologies, such as sensing, intelligence, reliability, endurance, etc. These technologies comprise the attributes that permit an autonomous system to make decisions in the framework of an operational mission. The study will assess the state of the art of autonomy and identify technical shortfalls or opportunities to significantly advance the capability. The goal is to identify where autonomy has high potential to enable Naval missions; however, implementation of autonomous systems also introduces operational challenges, such as affordability, policy, doctrine, etc. The study will also consider these factors and make recommendations to facilitate the introduction of autonomy capability into the Fleet. This study will be conducted at a classification level consistent with the information considered and the sensitivity of the study findings.

Specific tasking includes:

- Define/characterize "autonomy" as applied to Naval missions and identify contributing technologies to autonomy capability.

- Identify classes of autonomy for military applications, such as ISR, information management, decision making, logistics, weapon systems, etc. Particular emphasis will be placed on maritime systems and coordination between manned and unmanned systems that will potentially result in reduced manpower requirements, errors associated with processing, exploitation and dissemination and increased speed of data-from-sensor to information-to-decision maker/shooter (OODA Loop).

- Review relevant technologies and ongoing naval research and development (RDT&E) of autonomy systems/subsystems to evaluate the readiness of autonomy capability for introduction into maritime systems. Examine the potential for future technology opportunities to introduce autonomy capability into current, near-term of next generation systems. This examination should include technologies for

non-military applications, such as gaming, and international technology advances.

- Identify critical issues/barriers that impact the employment of autonomy in maritime systems, such as environmental, cultural, affordability, policy, doctrine, etc.

- Recommend technology solutions, investments and developments required to best leverage the use of autonomous systems in the maritime environment.

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Appendix D: Example Programs

These example programs relate to the chart on page XX in the main body of the report.

AIR:

RQ-7 Shadow: Currently operational, the RQ-7 Shadow unmanned aerial vehicle is used by the United States Army, Marine Corps, and other nations for reconnaissance, surveillance, target acquisition and battle damage assessment. Launched from a trailer-mounted pneumatic catapult, it is recovered with the aid of arresting gear similar to jets on an aircraft carrier. Its gimbal-mounted, digitally-stabilized, liquid nitrogen-cooled electro-optical/infrared camera relays video in real time via a C-band line-of-sight data link to the ground control station. It is manufactured by AAI Corporation.

MQ-4C Triton (also known as BAMS **-** Broad Area Maritime Surveillance unmanned aerial vehicle): The Northrop Grumman MQ-4C Triton is an unmanned aerial vehicle under development for the United States Navy. Developed under the Broad Area Maritime Surveillance program, the system is intended to provide continuous maritime surveillance for the U.S. Navy, and to complement the P-8 Poseidon, the multi-mission maritime aircraft. The system is expected to enter service in 2015.

AACUS (Autonomous Aerial Cargo / Utility Vehicle): AACUS is an ONR Innovative Naval Prototype (INP). The primary focus of AACUS is to develop advanced autonomous capabilities to enable unmanned and optionally manned vertical takeoff and landing systems that provide rapid response cargo delivery to distributed small units. AACUS will help push the technology of VTOL-based obstacle detection and avoidance and autonomous landing site selection and dynamic execution capabilities for unprepared landing sites, with goal-based supervisory control by field personnel.

Ground:

AEODRS (Advanced EOD Robotic System): The AEODRS will be a family of unmanned ground vehicles for use by Joint Explosive Ordnance Disposal forces to counter the threat posed by improvised explosive devices and unexploded ordnance. The AEODRS family of unmanned ground vehicles will consist of a dismounted operations variant, a tactical variant, and a base/infrastructure operations variant that share a common logical, electrical, and physical architecture and that are controlled by a common operator control unit. Systems will be comprised of components capable of being developed by independent entities within a competitive procurement process. Navy IOC is expected in FY16.

PackBot: is a series of military robots made by iRobot. The current variant is the PackBot 510 which uses a videogame-style hand controller to make it more familiar to young operators. More than 2000 are currently on station or were deployed in Iraq and Afghanistan. PackBots were the first robots to enter the damaged Fukushima nuclear plant after the 2011 earthquake in Japan. Some of the PackBot 510 variants are:

- Fast Tactical Maneuvering Kit utilized by infantry troops tasked with improvised explosive device inspection;

- First Responder Kit designed to help SWAT teams and other first responders with situational awareness;

- Hazardous Material Detection Kit collects air samples to detect chemical and radiological agents;

- "Fido" utilizes a payload in order to "sniff" out explosive materials. With the Fido, the PackBot has the capability of locating explosive devices and subsequently disarming them using on-board robotic capabilities;

- Sniper Detection Kit utilizes the Acoustic Direction Finder to localize gunshots with azimuth, elevation, and range.

Surface:

ACTUV (Anti-Submarine Warfare Continuous Trail Unmanned Vessel): The ACTUV program will develop and demonstrate an independently

deploying unmanned surface vessel optimized to provide continuous overt trail of threat submarines. The program has three primary objectives:

- Design, build, and demonstrate an experimental vessel based on clean sheet design approaches founded on the assumption that no person steps aboard at any point in its operating cycle, enabling beyond state-of-the-art platform performance characteristics.

- Demonstrate the technical viability of an independently deploying unmanned naval vessel under sparse remote supervisory control to enable a new class of maritime system.

- Demonstrate a game-changing ASW operational capability and facilitate rapid transition of that capability to the Navy in response to critical operational demand.

UISS (Unmanned Influence Sweep System): The UISS will provide the Littoral Combat Ship with a stand-off, long endurance, semi-autonomous minesweeping capability to counter acoustic and/or magnetic influence mine threats in the littoral environment. It will serve as a key part of Increment 3 of the Littoral Combat Ship's mine countermeasures mission package.

MUSCL (Modular Unmanned Surface Craft Littoral): MUSCL is a man-portable unmanned surface vehicle platform for riverine combatant craft support. It will be employed as a waterborne "point man" to increase situational awareness during operations on inland waterways. It supports the Navy Expeditionary Combat Command requirements and is capable of carrying different sensors and payloads to provide a variety of capabilities such as intelligence, surveillance, reconnaissance and threat detection.

SHARC (Sensor Hosting Autonomous Remote Craft): this operational wave glider is offered by Liquid Robotics on the world market. It is a platform that provides the user with autonomous, long dwell, low profile persistent ocean sensing. It converts wave energy into forward thrust and uses solar energy for navigation, C2, and sensing.

USSVs (Unmanned Sea surface Vehicles): these are ONR-developed vehicles that are used for experimentation. . The USSVs are clean-sheet designs, with an autonomous control system – optimized for missions and payloads anticipated by the Navy. More advanced autonomy, which will enable mission-level planning, perception-guided maneuvers and tactical behaviors, is currently in development. There are two basic vehicle types. The USSV-High Tow Force (HTF) is optimized for tow force, payload fraction, endurance and sea keeping and has transitioned to an acquisition program as a prototype. The USSV-High Speed (HS) is optimized for high speed in a sea way.

Undersea:

PLUS (Persistent Littoral Undersea Surveillance): PLUS was a successful ONR Innovative Naval Prototype program that demonstrated effective, adaptive and persistent undersea surveillance of multiple quiet targets over large littoral areas. PLUS is now a non-acquisition, user operational evaluation system. It is designed to detect and localize submerged targets. PLUS includes a cluster of netted unmanned underwater vehicles providing passive detection capability. A subsequent spiral will add UUVs with the Integrated Precision Underwater Mapping Array (iPUMA), providing an active search capability.

Knifefish: This is the Surface Mine Countermeasure Unmanned Undersea Vehicle (SMCM UUV). This program will address the Navy's need to reliably detect and identify undersea volume and bottom mines in high clutter environments and areas with potential for mine case burial. The SMCM UUV will gather environmental data to provide intelligence support for other mine warfare systems. This system will be a part of the LCS MCM Mission Package and will also be capable of operating from any craft of opportunity.

LBS-G (Littoral Battlespace Sensing) Glider: The LBS-G program provides a low-observable, continuous capability to characterize ocean properties that influence sound and light propagation for acoustic and optical weapon and sensor performance predictions. These buoyancy-driven undersea gliders will enable anti-submarine, mine, expeditionary, and naval special warfare planning

and execution and persistent intelligence preparation of the environment. Launched and recovered from oceanographic survey vessels, LBS-G will expand the survey capability of survey vessels in contested areas.

LDUUV (Large Displacement Unmanned Undersea Vehicle): The LDUUV is an ONR Innovative Naval Prototype program that will develop fully autonomous, long-endurance, land-launched unmanned undersea vehicles capable of operating near shore. It will develop the critical technologies needed to enable UUVs to operate and survive in the littorals for 70+ days. The LDUUV is a pier-launched and recovered UUV (without the need for ship-launch or recovery) with the capability to transit in the open ocean and conduct over-the-horizon missions in littoral waters. The LDUUV program will develop new air independent energy systems and core vehicle technologies to extend unmanned undersea vehicle endurance into months of operation. Advanced autonomy and sensing will enable operation in the cluttered littoral environment.

Information:

DTCWC (Dynamic Time Critical Warfighting Capability): The DTCWC program (originally an Air Force program) fuses a variety of sensor inputs to detect, locate, classify, and report on a specific set of high-value, time-sensitive ground targets in a tactically actionable timeframe. Designed to analyze intelligence and verify its potential accuracy, the DTCWC works faster than human analysis. The platform's mission is to augment intelligence analysts, not replace them. Its mathematic calculations take minutes instead of days or weeks to sort through data and send it back to command centers.

Appendix E: Acronyms

A2/AD	Anti-Access/Area Denial
AACUS	Autonomous Aerial Cargo/Utility Systems
ACRS	Area Clearance Rate Sustained
ACTUV	Anti-Submarine Warfare Continuous Trail Unmanned Vessel
AEODRS	Advanced Explosive Ordnance Disposal Robotic System
AI	Artificial Intelligence
ASN RDA	Assistant Secretary of the Navy for Research, Development and Acquisition
BAMS	Broad Area Maritime Surveillance
C2	Command and Control
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, Reconnaissance
CARACaS	Control Architecture for Robotic Agent Command and Sensing
COLREGS	Collision Regulations at Sea
COTS	Commercial Off-The-Shelf
CNO	Chief of Naval Operations
CNR	Chief of Naval Research
CONOPS	Concept of Operations
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
DON	Department of the Navy
DOTMLPF	Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel and Facilities
DTCWC	Dynamic Time Critical Warfighting Capability
FAA	Federal Aviation Administration
GPS	Global Positioning System
IED	Improvised Explosive Device
IOC	Initial Operating Capability
ISR	Intelligence, Surveillance, and Reconnaissance
JPL	Jet Propulsion Laboratory
LBS	Littoral Battlespace Sensing (gliders)
LCS	Littoral Combat Ship
LDUUV	Large Diameter UUV
LOS	Law of the Sea
MCM	Mine Countermeasures

MOAA	Maritime Open Architecture Autonomy
MOOS-IvP	Mission Oriented Operating Suite - Interval Programming
MUSCL	Modular Unmanned Surface Craft Littoral
N2/N6	Deputy Chief of Naval Operations for Information Dominance
NAVAIR	Naval Air Systems Command
NAVSEA	Naval Sea Systems Command
NRAC	Naval Research Advisory Committee
NRL	Naval Research Laboratory
ONR	Office of Naval Research
OPNAV	Office of the Chief of Naval Operations
PEO	Program Executive Officer
PLUS	Persistent Littoral Undersea Surveillance
PM	Program Manager
POR	Program of Record
R&D	Research and Development
RDT&E	Research, Development, Test & Evaluation
ROS	Robot Operating System
S&T	Science and Technology
SECNAV	Secretary of the Navy
SHARC	Sensor Hosting Autonomous Research Craft
SLOCs	Sea Lines of Communication
SSG	CNO's Strategic Studies Group
TOA	Total Obligation Authority
TOR	Terms of Reference
UAS	Unmanned Aircraft System
UGV	Unmanned Ground Vehicle
UISS	Unmanned Influence Sweep System
USV	Unmanned Surface Vehicle
USSV	Unmanned Sea Surface Vehicle
UUV	Unmanned Underwater Vehicle