Marine Robotics: Opportunities for the Commonwealth of Massachusetts

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Framing the Marine Robotics Market

Massachusetts leads the newest and most promising segment of Marine Robotics, the research, development and commercial manufacture of Autonomous Underwater Vehicles. Two classes of platforms dominate the Marine Robotics industry today, Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs). ROVs share similarities to drone aircraft, in that they are continuously controlled by a team of human operators. Because radio waves do not penetrate seawater, ROVs are tethered to ships, which house the operators and which provide power and communications to the vehicles. AUVs operate without a tether, allowing them much greater freedom of motion, but also imposing the requirements that they be capable of operating without direct human control and that they carry their own power source. AUVs are a newer technology, enabled by advances in computers, software, sensors, and batteries. While the market for AUVs is currently less than ROVs, its growth is projected to be greater for the foreseeable future.

ROVs capable of operating at several thousand meters depth once existed only at Woods Hole Oceanographic Institution and a few other advanced operational organizations. Today ROVs are essential operational elements of off-shore oil and gas production, used for drilling support, installation of subsea equipment, ongoing inspection and maintenance, and decommissioning. The 2013 market for ROVs operations is variously estimated from $1.6B[1] and $2.5B[2]. ROV production is global in nature. Massachusetts firms provide many ROV components, and produce some of the smaller classes of ROVs, but is not a large player in the current ROV market.

The AUV market is very young, with AUVs taking root in industry and the military in the last decade and a half or so. Because AUVs must operate in challenging environments with minimal or no human supervision, the vehicles are dependent on sophisticated software and sensors. The state-of-the-art of AUV technology continues to evolve rapidly, with vehicle capability and reliability improving significantly every year. While many research laboratories experiment with AUV technology, comparatively few organizations can build operational systems. The total number of AUVs produced in 2009 was estimated at 629 by Westwood[3] and the total AUV market value in 2014 at $457M[2]. As described earlier, Massachusetts organizations currently dominate the design and construction of AUVs.

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[1] Symes, K., 2013. "Rise of the Work Class ROV Market," Marine Technology Reporter, November/December 2013, pp 30-33.

[2] VISIONGAIN, ROVS in the Oil and Gas Market 2013-2030,

[3] Westwood, J., 2010. The AUV market place. Oceanology International, London, 10th March. http://www.douglas-westwood.com/files/files/532-100310%20OI%20London%20JW.pdf

Marine Robotics is both a distinct industrial sector and an enabling technology for many industries, to adapt a phrase from the "Massachusetts Robotics Revolution"[4]. Currently the AUV market is dominated by vehicles which survey the seafloor and ocean conditions. However, continued advances in technology and capabilities are opening new, larger markets, such as inspection, repair and maintenance of infrastructure (IRM). At the recent AUVSI conference, a commercial AUV service supplier called 2014 the 'year of pipeline inspection,' as this is the year in which AUV pipeline inspection is becoming a routine commercial offering (by his company, at least), with the new AUVs completing surveys six times as fast as the earlier technology with corresponding savings in ship time. In brief, the introduction of more capable systems feeds a virtuous circle, where new robotic capabilities enable new industry markets, which in turn drive technology investment in robotics. Deep sea mining provides yet another example as this potentially enormous robotics market is in its infancy.

A new market of hybrid vehicles is emerging with great commercial potential. These vehicles combine attributes of ROVs and AUVs; for example some vehicles have teleoperated and fully autonomous modes of operation. The software intensive nature of hybrid vehicles, and their dependence of onboard batteries, means these vehicles share far more in common with AUVs than with ROVs. WHOI has pioneered a class of hybrid systems with the creation of the Nereus class vehicles[5], which use very small, potentially expendable fiber optic tethers. Other, less mature technologies include resident vehicles which fly to seafloor infrastructure, dock, and then operate as an ROV once connected to the power and communications on the seafloor. Hybrid vehicles substantially reduce ship costs, take on inspection tasks formerly carried out by ROVs, and enable a new monitoring market.

Strength of the Massachusetts Marine Robotics Cluster

Marine robotics lies at the intersection of two strong business clusters in Massachusetts, the Marine Robotics Cluster, and the Marine Technology Cluster. The annual sales of companies in the Massachusetts Robotics Cluster were reported at $1.9B in 2011 with 2,300 people employed[6]. Sales by Massachusetts marine technology companies were estimated at $1.5B in 2007 by Curry[7], with $4.8B in the larger New England area. The leading manufacturers of AUVs are all located in the state: Kongsberg Hydroid, Teledyne Benthos, and Bluefin Robotics. These companies are directly tied to the strong Marine Robotics research community in Massachusetts, the first two having spun out of WHOI, and the last from MIT. An AUV, complete with its supporting equipment, can cost from $100k to $7M. The more expensive AUVs are used for deep-water survey (mostly oil and gas) and for military applications

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[4] Massachusetts Technology Leadership Council (MASSTLC), 2013. The Massachusetts Robotics Revolution.http://c.ymcdn.com/sites/www.masstlc.org/resource/resmgr/annual_reports/masstlc_robotics_final_web.pdf

[5] Bowen, A. D., Yoerger, D. R., Taylor, C., McCabe, R., Howland, J., Gomez-Ibanez, D., ... & Jakuba, M. V. 2009. The Nereus Hybrid Underwater Robotic Vehicle for Global Ocean Science Operations to 11,000 m Depth. In *Proc. OCEANS* (Vol. 8).

[6] Massachusetts Technology Leadership Council (MASSTLC), 2013. The Massachusetts Robotics Revolution. http://c.ymcdn.com/sites/www.masstlc.org/resource/resmgr/annual_reports/masstlc_robotics_final_web.pdf

[7] Curry, T.J.; Merrill, M.L.; Andrade, S.P.; Peterson, S.B.,2008. "Development of the Marine Science and Technology industry cluster in New England," OCEANS 2008 , vol., no., pp.1,9, 15-18.

(mostly mine countermeasures). The low cost portion of the AUV market is growing rapidly. For example Ocean Server (in Fall River) manufactures a small, low cost entry in the AUV market that is gaining traction, with approximate 250 small AUV sales already. Other manufactures of underwater robotic systems in Massachusetts include Lockheed Martin Sippican which builds AUV training targets.

Although estimates of the total size of the AUV market vary widely, our discussions conservatively identify AUV sales revenues of approximately $70-100M/year in 2013 by Massachusetts companies. Expenditures on research and operations substantially add to that number, as do sales of associated equipment and software. Market studies have significantly higher market valuations, for example estimating the global AUV market in 2013 at $457M[8], which is possible when AUV operations are factored in. We anticipate that existing AUV markets will continue to expand, however the next leap in growth will come by enabling much larger markets answering unmet needs in offshore oil and gas production, infrastructure inspection, deep-ocean mining, environmental assessment, as well as new government and naval applications. Estimates of growth are challenging, largely due to uncertainty in timing associated with new markets. One widely cited study projects a likely total AUV market size of $1.8 billion by 2017 with a 'high side' number of $3.7 billion[9].

While Marine Robotics, especially AUVs, have been largely spawned from the ocean science enterprise, their applications are primarily to defense and commercial markets. This is part of a larger transformation of the marine instrumentation industry. Many of the early marine instrument companies that spun out of WHOI commercialized some oceanographic technology, and then sold that capability back to the larger ocean science community. AUVs are being used for applications like mine countermeasures and site survey for oil and gas infrastructure, in addition to their oceanographic uses. As outlined below, ocean science uses of AUVs is for most companies the smallest of the three market segments, with defense the largest, and commercial in the middle but growing quickly.

Market assessments uniformly project substantial growth in Marine Robotics sales and service, but especially in the AUV market. Westwood[10] projects that deployed AUV systems will increase 40% over the period 2014-2018. The MarketandMarket[11] report projects strong growth in the marine robotic market, with AUV growth at 32% CAGR and ROV market growth of 20% CAGR. Composition of the AUV market is expected to change. At present military sales comprise the largest fraction of most manufacturer's sales, ranging from 50-75%. Most military sales are to the US government. Over the next five years, sales to non-US militaries are expected to grow faster than US military sales. Similarly, commercial sales are also expected to expand more rapidly than defense sales.

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[8] Marketsandmarkets.com, 2014. "Unmanned Underwater Vehicles Market by Product (Autonomous Underwater Vehicle, Remotely Operated Vehicle), Application (Defense, Oil and Gas, Scientific Research), Region & Country - Global Trends & Forecasts to 2014 – 2019", Report Code: AS 2327, http://www.marketsandmarkets.com/Market-Reports/unmanned-underwater-vehicles-market-140710720.html

[9] Westwood, Douglas, The AUV Gamechanger Report.

[10] Douglas-Westwood, 2014. "World AUV Market Forecast 2014-2018", ISBN 9-781-9100-45-01-5, http://www.douglas-westwood.com/shop/shop-infopage.php?longref=1423~0#.VFksD1d1Pbw

[11] Marketsandmarkets.com, 2014. Ibid.

For Massachusetts, the rise of more advanced AUVs and hybrid vehicles capable of Inspection, Repair and Maintenance (IRM) is a tremendous opportunity: operationally they shift market value from ships and ROVs to AUVs, and thus play to the region's strengths. IRM expenditures for oil and gas platforms and for undersea pipelines was $2.8B in 2010[12]. A large fraction of this value is captured by ship operators, with 92 ships serving this market.

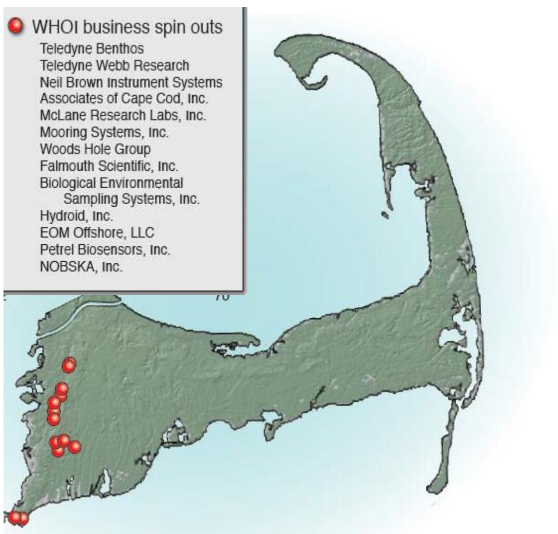

Figure 1: Spinoff companies from Woods Hole Oceanographic Institution. One of the primary goals of the new WHOI Center for Marine Robotics is to foster new business enterprises on the Cape and in Massachusetts. As Marine Robotics enters mainstream commercial and military use, the platform-oriented spinoffs (e.g. Teledyne Webb and Benthos, Kongsberg Hydroid, and off-Cape Bluefin Robotics and Sippican) largely service emerging military and commercial markets. Benefits ripple through the ecosystem, for example instrumentation companies increasingly adapt their product line to serve the growing Marine Robotic market.

One measure of growth potential for the small marine robotic companies is that the WHOI and MIT spinoffs have all been acquired, and are now part of much larger organizations. Bluefin was purchased by Battelle Memorial Institute, Webb by Teledyne (now part of their Teledyne Benthos operation), and Hydroid by Kongsberg. Sippican, the manufacturer of AUV training targets was acquired by Lockheed Martin, Inc. In every case operations remain in Massachusetts. These acquisitions bring additional investment to the region, and the liquidity events associated with the purchase of these companies makes it easier for subsequent Marine Robotics startups in the region to attract talent and investment.

Massachusetts has a particularly strong position with respect to its robotics research ecosystem (see figure 2) with substantial overlap between Marine Robotics and other robotics activities. Robotics programs at many of the 35 local robotics research programs either work on, or cross-pollinate with, Marine Robotics research. For example, at one local school faculty in the Aero-Astro Department work on autonomy for AUVs. The autonomy used for most AUVs has its roots in the AI approaches pioneered by Rodney Brooks at MIT. Emerging inspection and monitoring marine robots leverage vision and manipulation investments made in the terrestrial robotics community. Marine Robotics is a source of unique innovation as well, for example the undersea environment forces the development of mobile robotic systems capable of operating without human supervision. Navigation is another area where undersea navigation challenges (GPS does not work underwater) is driving innovation in the form of development of Simultaneous Localization and Mapping (SLAM) algorithms that are broadly applicable, for example to self-driving cars.

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[12] Jason Wadie, 2011. "The Global IRM Sector," Subsea Asia Conference, Kuala Lumpur, 2nd June 2011. http://www.subseauk.com/documents/subsea%20asia%20-%20jason%20waldie.pdf

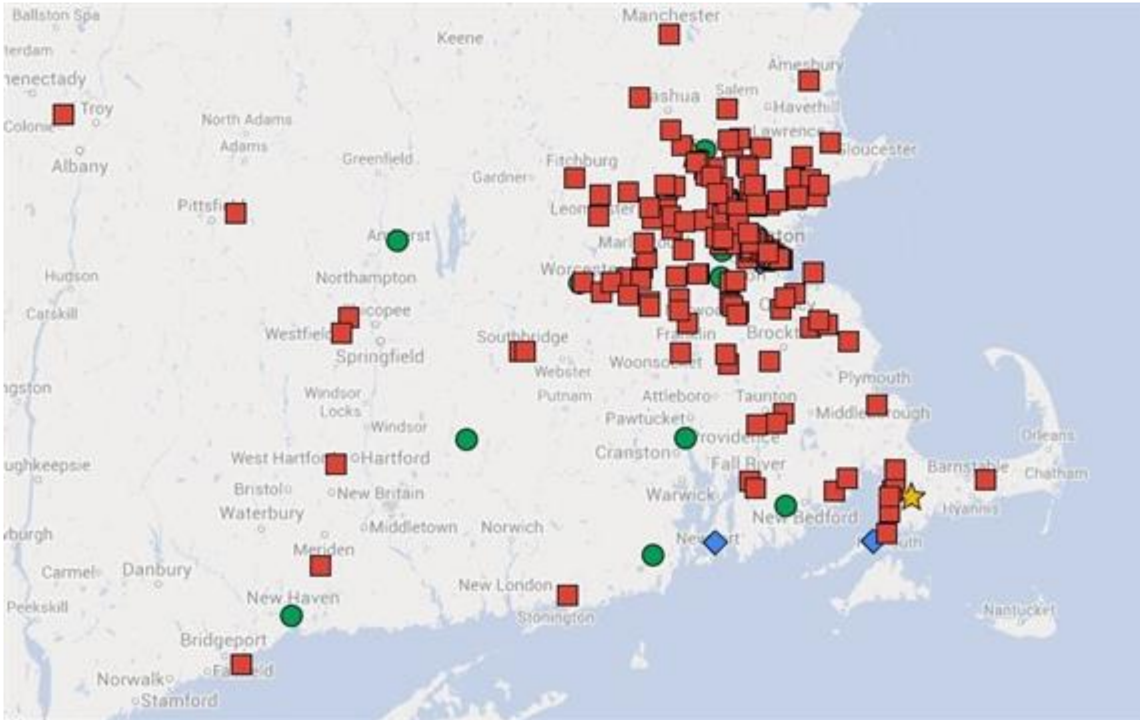

Figure 2: The Massachusetts Robotics ecosystems, from the Massachusetts Technology Leadership Council web site. Companies are depicted as red boxes, research institutions as blue diamonds, universities as green circles, and test sites as stars. Note the cluster of robotics companies to the South East, especially Cape Cod, which is composed primarily of Marine Robotics organizations. Particularly relevant to this proposal is the fact that the only listed test site is for air vehicles, and is on Cape Cod. Our proposal is to create testing facilities tailored for the next generation of Marine Robotics systems, and would ultimately add another star to this map.

Market Growth Opportunities

Growth of the Marine Robotics market is driven by the growth of industrial activities in the marine environment, particular in extractive industries, and the increasing demanding threat environment in which naval forces must operate. Prospects for long term growth of the Marine Robotics market are extremely good, being driven by expansion of existing uses, new uses of robotic systems in existing markets, and the creation of new markets. For example, figure 3 shows the trend in oil and gas discoveries underlying 'peak oil', in which reservoir discoveries are now dominated by the offshore segment[13]. This suggests promising future for Marine Robotics, since production in deep-water is completely dependent on ROVs today, and planning for the future emphasizes increased use of AUVs. Other large trends with implications for Marine Robotics include the move towards deep sea mining, growth of infrastructure monitoring activities, increasing in aquaculture activity, increasing installation of marine wind and wave energy facilities, growth in submarine cables, and more.

[13] LUKOIL, 2014. Global Trends on Oil and Gas Markets to 2025, http://www.lukoil.com/materials/doc/documents/Global_trends_to_2025.pdf

Science uses of ROVs, AUVs, and hybrid systems are extremely promising, and continue to motivate innovative research and development activities. However, these uses are not emphasized here, as the science market is small compared to commercial and military markets.

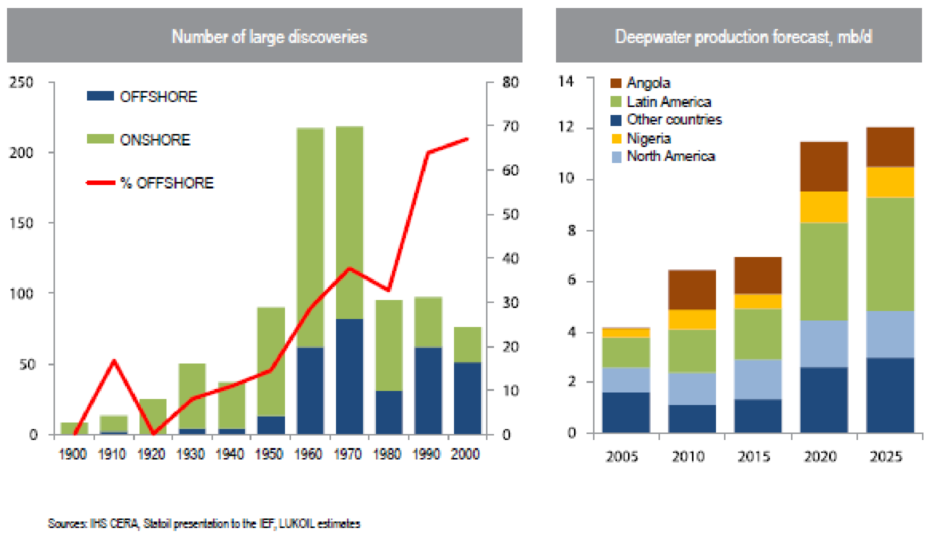

Figure 3: Trends in offshore discovers and production, highlighting the growing important of offshore oil supplies.

Mine Countermeasures (MCM): One of the first naval applications of AUVs has been mine countermeasures. Hydroid REMUS 100 vehicles were used to clear mines in Umm Qasr's port at the early stages of Operation Iraqi Freedom[14]. Currently 18 Explosive Ordinance Division (EOD) units are equipped with AUV capability for port security and mine clearance. More recently, the US Navy selected the General Dynamics Knifefish program, which uses a larger Bluefin AUV with a sophisticated new class of sonar, as the mine countermeasures mission package for the Littoral Combat Ship[15]. Various sophisticated AUVs with capabilities such as onboard detection and classification of mine-like targets are in development. Substantial funding has been directed by the Navy towards this need, and to some degree the Naval MCM R&D has provided the seed investment for Massachusetts Marine Robotics community. However, as described below, larger markets are emerging.

Site Survey: Infrastructure installations in the offshore environment, especially deep-water oil and gas production equipment, require accurate maps and seafloor hazards assessment to plan infrastructure placement. AUVs are now a preferred tool for deep-water site surveys, and this comprises the larger part of the commercial AUV service market. Day rates for the full AUV survey capability (including the ship) are reported to be in excess of $100k/day for deep-water surveys. With oil and gas moving to deeper water, and the introduction of new offshore infrastructure activities such as offshore wind and wave energy farms, the site survey market is expected to continue to grow for the foreseeable future. Companies offering AUV survey capabilities include Fugro Survey, C&C Technologies, Tesla Offshore, Phoenix Offshore Marine, NCS Survey, Atlas Maridan, and DOF Subsea.

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[14] REMUS, http://www.whoi.edu/main/remus
[15] Knifefish / Artemis, http://www.navaldrones.com/knifefish.html

Inspection, Repair and Maintenance: These activities might be thought of as more analogous to the recent DARPA Disaster Response Grand Challenge[16] where robots must carry out manipulative tasks in cluttered and complex environments. In the case of the undersea robot, the complex underwater environment is subsea oil and gas completion hardware on the seafloor, pipelines on the seafloor, the hull of a ship, or a hydrothermal vent on a mid-ocean ridge. The ability for autonomous and lightly supervised systems to carry out tasks safely in such locations is central to the largest market opportunity on the horizon – Inspection, Repair and Maintenance (IRM) of undersea infrastructure[17]. This market promises to dwarf the existing AUV markets, as the combination of the recent Deepwater Horizon disaster and increasing complexity of subsea equipment are driving a need for greater monitoring and maintenance activities. The DeepStar project is an example of an industry consortium that is developing advanced IRM activities[18]. Pipeline inspection is now a commercial AUV service offering. The HULS program is an example of a $30M Navy procurement program for an autonomous (although tethered) ship hull and pier inspection robot lead by Bluefin Robotics in Quincy[19].

Environmental Awareness: Sensing dynamic ocean conditions is important for a range of scientific, military, and commercial activities. Military markets are driven by factors such as the importance of sound propagation conditions for undersea warfare, which in turn depend on physical ocean conditions. Commercial drivers include the sensitivity deep water drilling to subsurface currents, and the need for environmental information in the case of a disaster such as the Deepwater Horizon incident or oil spill. The military part of this market involves direct sales of vehicles and support equipment to the Navy. For example, the Littoral Battlespace Sensing-Glider (LBS-G) Program acquired 150 underwater gliders (a form of AUV that propels itself via buoyancy changes) in a $53M acquisition and is acquiring another 150 more from Teledyne Benthos in North Falmouth[20]. Oil and gas service companies have just started offering glider operations as a service, so the size of this market is small but growing.

Search, Salvage, and Assessment: The ability to find platforms lost at sea and to survey the sites of undersea disasters supports such diverse needs as aviation safely and recovery from environmental disasters. AUVs have featured prominently in the response to recent aviation disasters over the ocean. The epic search for Air France Flight 447 culminated in the discovery of the wreckage by REMUS 6000 vehicles, designed and operated by WHOI[21]. More recently, a Bluefin-21 vehicle, built by Bluefin Robotics in Quincy, was the first deep mapping capability deployed to search for Malaysian Airlines

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[16] The DARPA Robotics Challenge, http://www.theroboticschallenge.org/

[17] AUV Panel Announcement: Autonomous Underwater Vehicles (AUVs) for Oil & Gas Applications, http://auvac.org/newsitems/view/1769

[18] Jacobson, John, Pierce Cohen, Amin Nasr, Art J. Schroeder, and Greg Kusinski. 2013. "DeepStar 11304: Laying the Groundwork for AUV Standards for Deepwater Fields." *Marine Technology Society Journal* 47, no. 3: 13-18.

[19] Bluefin Robotics Awarded $30M Hull Unmanned Underwater Vehicle Localization System (HULS) Production Option, http://www.bluefinrobotics.com/news-and-downloads/press/HULS-awarded/

[20] Sole Source - Littoral Battlespace Sensing Glider, https://www.fbo.gov/index?s=opportunity&mode=form&id=95d194d2195a88efc1cea368e7d0e1ec&tab=core&_cview=1

[21] Purcell, M.; Gallo, D.; Packard, G.; Dennett, M.; Rothenbeck, M.; Sherrell, A.; Pascaud, S., 2011. "Use of REMUS 6000 AUVs in the search for the Air France Flight 447," *OCEANS 2011* , pp.1,7, 19-22 Sept 2011.

Flight[22] 370. Over $100M has been set aside by the Australian and Malaysian governments to fund the ongoing search[23]. Other needs include the ability to assess the state of undersea infrastructure following undersea earthquakes, tsunamis, and extreme weather events. Hurricanes Katrina and Irene caused heavy damage to oil and gas infrastructure in the Gulf of Mexico, including the 50,000 km of subsea pipeline[24].

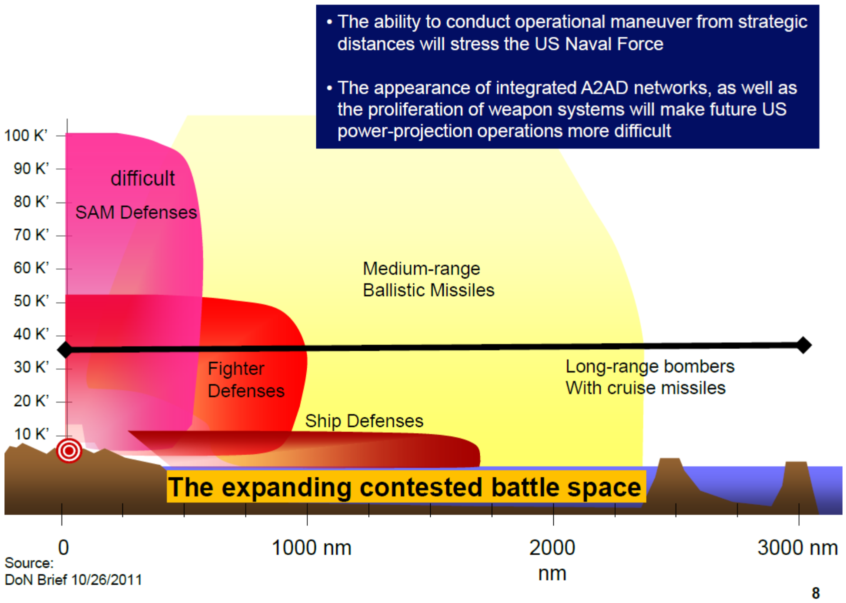

Figure 4: The future US Navy will have to operate in a high-threat environment to carry out its core missions. This graphic, from the NRAC 2012 Autonomy Study depicts the problem, generally described as the A2AD problem (Anti-Access, Area Denial). Unmanned systems in both the air and the sea are increasingly identified as a promising technology for countering these threats.

New Naval Application of Marine Robotics: Recent high-level studies by the Defense Science Board and the Naval Research Advisory Committee suggest that autonomous undersea systems will revolutionize naval warfare[25,26]. At the most abstract level, such projections come from the observation that the Navy will face unprecedented threats to its ability to maintain presence in many regions of the world (see figure 4). Unmanned systems offer the potential to counter these threats, for example potentially providing certain AntiSubmarine Warfare (ASW) capabilities. Consequently, commitment to robotic systems extends to the highest levels, with Chief of Naval Operations, Admiral Greenert stating:

> *(We need) to move ahead with unmanned vehicles in the undersea domain. This year, I want to lay out a road map for the future where we have milestones. That technology is out there, we've*

[22] Malaysia Airlines Flight 370 search goes deep with Bluefin 21 robotic sub as black boxes fall silent, Associate Press, April 14, 2014, 1:43 AM, http://www.cbsnews.com/news/malaysia-airlines-flight-370-search-bluefin-21-robotic-sub-black-boxes-silent/

[23] New technology used in next phase of search for Malaysia Airlines Flight 370, Posted 6:05 am, October 6, 2014, by CNN Wire, http://whnt.com/2014/10/06/new-technology-used-in-next-phase-of-search-for-malaysia-airlines-flight-370/

[24] Cruz, A. M., & Krausmann, E. (2008). Damage to offshore oil and gas facilities following hurricanes Katrina and Rita: an overview. *Journal of Loss Prevention in the Process Industries*, *21*(6), 620-626.

[25] Naval Research Advisory Committee (NRAC) 2012. "How Autonomy Can Transform Naval Operations," http://www.nrac.navy.mil/docs/NRAC_Final_Report-Autonomy_NOV2012.pdf

[26] Defense Science Board (DSB) 2012. "The Role of Autonomy in DoD Systems," http://fas.org/irp/agency/dod/dsb/autonomy.pdf

done demonstrations in the lab or in a docile bay. We're going to take this to the ocean on a mission, a specific exercise, as a road map to commit ourselves to certain things.[27]

Deep Sea Mining: Mining of the deep ocean is attracting substantial investment. Motivations range from the economic to the political. The high content and ease of extraction of valuable metals from some marine deposits make mining in the deep sea an attractive economic proposition, spawning companies like Nautilus Minerals[28]. Other motivations include the desire by some countries, for example Japan, to free themselves of dependence on foreign suppliers of key minerals. Since Japan does not have terrestrial resources, it turns to the ocean. Deep sea mining creates potentially significant environmental risks. Exploration, mining, and environmental impact monitoring activities are likely to be robot intensive.

The Long View

Like the transition from sail to steam power, the advent of Marine Robotic systems usher in a new chapter in human interaction with the ocean. Robotic systems open the deep ocean to routine access, allowing commercial extraction of minerals on and under the seafloor. They allow scientists to move beyond occasional visits to the ocean, enabling a persistent pervasive presence from coastal water to the remote Arctic. The transformation of naval warfare by Marine Robotics is already beginning, although the ultimate impact is impossible to predict. In short, large changes are coming, and these changes will create both great economic opportunity and disruption.

Massachusetts has a proud maritime history, from the age of sail through the advent of steam, to the construction of the first nuclear powered ships. The Bethlehem Fore River shipyard employed 32,000 people at its peak. However, that pinnacle had its roots in a steam engine company founded by John Watson, 60 years earlier in the 1880s. Quincy shipyard was the among the busiest in the country, producing over 112 ships, including 5 aircraft carriers during World War II[29]. However the shipyard declined after the war, closing in 1986. Today Massachusetts maritime history is being reborn, in the form of numerous small Marine Robotics companies, one of them even located at the old Fore River Shipyard. Our Commonwealth is well placed because we have a foundation of small, highly innovative companies, and a vibrant research community. Competition from other regions will be fierce, as the growing value of the Marine Robotics market becomes evident. Our proposal is designed to build infrastructure in Massachusetts that will strengthen Marine Robotics activities here, and foster a closer relationship between local research and business institutions. With government, academia, and industry working together, we believe that the Massachusetts Marine Robotics revolution will surpass the previous high-water mark of Massachusetts maritime industry.

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[27] The CNO on the Evolution of the USN: Robots, Ships, USMC Collaboration and the Arctic, February 1, 2014. http://www.sldinfo.com/the-cno-on-the-evolution-of-the-usn-robots-ships-usmc-collaboration-and-the-arctic/

[28] Solwara 1 Project: High Grade Copper and Gold, http://www.nautilusminerals.com/s/Projects-Solwara.asp

[29] http://www.shipbuildinghistory.com/history/shipbuilders.htm