REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*: 29-05-2018

2. REPORT TYPE: Final

3. DATES COVERED *(From - To)*: 21 JUL 2017-15 JUN 2018

4. TITLE AND SUBTITLE

Future UNREP: Existing Technologies, Concepts of Operation, and Why Replenishment at Sea Must Evolve

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Jones, Richard D., CDR, SC, USN

Paper Advisor: Dr. William Bundy and Mr. Walter Bonilla

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Gravely Naval Research Group
Naval War College
686 Cushing Road
Newport, RI 02841-1207

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

None

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION A. Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES

A paper submitted to the Naval War College faculty in partial satisfaction of the requirements of the Gravely Naval Research Group. The contents of this paper reflect my own personal view and are not necessarily endorsed by the NWC or the USN.

14. ABSTRACT

The United States Navy currently operates in an environment not experienced since the Second World War and faces an evolving future that will continue to grow in complexity and competition. While the past almost three decades have allowed U.S. naval forces to deploy globally and operate virtually uncontested and with impunity, the future environment will no longer allow such dominance without a consistent and credible challenge. In order for the U.S. to maintain both offensive and defensive superiority across all warfare domains and to meet these influential forces head on, a departure from and re-imagining of current processes and operations is paramount. In order for effective logistics sustainment, as well as future combat effectiveness in the Pacific with the rise of China, the concept of underway replenishment must evolve. Furthermore, existing technologies such as undersea basing, autonomous undersea vehicles, autonomous shipping, and additive manufacturing/three dimensional printing may offer the increased flexibility and agility needed for effective logistics sustainment.

15. SUBJECT TERMS

At-Sea Replenishment

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCLAS	UNCLAS	UNCLAS		38	Dr. William F. Bundy, Director, Gravely Group
					19b. TELEPHONE NUMBER *(Include area code)* 401-841-2674

Reset

This Page Intentionally Left Blank

Future UNREP: Existing Technologies, Concepts of Operation, and Why Replenishment at Sea Must Evolve

The Gravely Research Group
Richard D. Jones
CDR, USN

A paper submitted to the Faculty of the United States Naval War College Newport, RI in partial satisfaction of the requirements of the Gravely Group.

May 28, 2018

Contents

Tables and Charts

Abstract

The United States Navy currently operates in an environment not experienced since the Second World War and faces an evolving future that will continue to grow in complexity and competition. While the past almost three decades have allowed U.S. naval forces to deploy globally and operate virtually uncontested and with impunity, the future environment will no longer allow such dominance without a consistent and credible challenge. In order for the U.S. to maintain both offensive and defensive superiority across all warfare domains and to meet these influential forces head on, a departure from and reimagining of current processes and operations is paramount. More specifically, increasing competition and contested operations will significantly impact the characteristics and processes of U.S. Navy supply, sustainment, and underway replenishment operations. In order for effective logistics sustainment, as well as future combat effectiveness in the Pacific with the rise of China, the concept of underway replenishment must evolve. Furthermore, existing technologies such as undersea basing, autonomous undersea vehicles, autonomous shipping, and additive manufacturing/three dimensional printing may offer the increased flexibility and agility needed for effective logistics sustainment.

Introduction and Background

"The world is experiencing some deeply disturbing technical, economic, and geopolitical shifts that pose potential threats to US preeminence and stability." - Arati Prabhakar, DARPA[1]

The United States Navy currently operates in an environment not experienced since the Second World War, and faces an evolving future that will continue to grow in complexity and competition. While the past almost three decades have allowed U.S. naval forces to deploy globally and operate virtually uncontested and with impunity, the future environment will no longer allow U.S. dominance without a consistent and credible challenge. The reemergence of Russia and persistent threats from North Korea and Iran continue to complicate global security and stability, as do non-state actors and violent extremist organizations. Most significant though is China's continued rise as it threatens the balance of power in the current unipolar world which sees the U.S. as the dominant influence. Furthermore, this new reality forces the U.S. to readdress its defense strategy across all warfare domains, especially in the Pacific. These realities continue to complicate global security and the ability to maintain maritime superiority and are further addressed in the 2018 National Defense Strategy (NDS).[2]

In the 2016 Design for Maintaining Maritime Superiority, the Chief of Naval Operations discusses three global and influential forces concerning security, including the increase in maritime traffic, the global information system, and the rate of technological creation and adoption.[3] Nowhere will this be more evident than in the Asia-Pacific region with a rising China. In order for the U.S. to maintain both offensive and defensive

---

[1] Arati Prabhakar, "Breakthrough Technologies for National Security," *Defense Advanced Research Projects Agency (DARPA)*, *Tech. Rep.* (2015)., accessed February 23, 2018, https://www.darpa.mil/attachments/DARPA2015.pdf

[2] United States, Department of Defense, National Defense Strategy Summary, Washington D.C.: Department of Defense, 2018.

[3] John M. Richardson, "A Design for Maintaining Maritime Superiority," Naval War College Review 69, no. 2 (2016).

superiority across all warfare domains and to meet these influential forces head on, a departure from and reimagining of current processes and operations is paramount. More specifically, increasing competition and contested operations will significantly impact the characteristics and processes of U.S. Navy supply, logistics and sustainment, and underway replenishment operations. Verbiage provided in the 2018 NDS such as “resilient and agile logistics,” “non-commercially dependent distributed logistics and maintenance,” “advanced autonomous systems” and “adaptive basing” sets the foundation for the direction of future logistics and concepts of operations.[4]

The realities and implications of peer and near-peer competitors, as well as strategic guidance given such as the NDS and the Design for Maintaining Maritime Superiority, raise several questions about future logistics concepts of operations. If the future of the Navy includes a 355 platform fleet regardless of the mixture of manned or unmanned platforms, what are the logistics implications in order for effective sustainment? What role will technology and unmanned logistics platforms play in at-sea sustainment, such as autonomous cargo shipping? This paper posits that in order for effective logistics sustainment, as well as future combat effectiveness in the Pacific with the rise of China, the concept of underway replenishment must evolve. Furthermore, existing technologies such as undersea basing, autonomous and unmanned undersea and surface vehicles, and additive manufacturing/three dimensional printing may offer the increased flexibility and agility needed for effective logistics sustainment. The goal of this paper is to exam some existing and emerging technologies and how those may be applied to underway replenishment capabilities to support strategic guidance and position the Navy to meet future challenges and threats.

---

[4] United States, Department of Defense, National Defense Strategy Summary, Washington D.C.: Department of Defense, 2018.

This paper is organized in three main sections. The first section will discuss current strategic guidance addressing future challenges and priorities and sets the stage for the concepts that formulate the possibilities of future underway replenishment operations. The second section explores existing technologies and platforms. These include undersea basing, unmanned undersea vehicles, autonomous cargo shipping, and additive manufacturing/three dimensional printing. Additionally, this section will include a future concept of at-sea replenishment operations utilizing the potential of existing technologies. While the concepts that will be discussed may seem unrealistic, non-efficient, or cost effective, the author's intent is to stimulate thought and discussion regarding future logistics in the realm of replenishment and sustainment at sea, especially in a strategic environment that continues to grow in complexity. The third and final section focuses on internal and external threats. The internal threats include the challenges of speed, agility, innovative industry partnerships, and a lack of focused and consolidated effort on future logistics concepts. The external threat discussed is the challenge of a rising China. These threats are discussed at length due to the complexities of the issues, the risks to U.S. dominance and security, and a decreasing U.S. competitive edge that complicates the ability to overmatch potential adversaries.

Strategic Guidance

The 2018 National Defense Strategy (NDS) describes the "challenges to the U.S. military advantage" and how near-peer competitors such as China, and revisionist powers such as Russia, are affecting and changing the global security environment, the balance of power, and current world order.[5] Furthermore, the NDS states that the "rapid technological

[5] United States, Department of Defense, National Defense Strategy Summary, Washington D.C.: Department of Defense, 2018.

advancements and the changing character of war" is also affecting the current and future strategic security environment.[6] The NDS describes key areas that highlight the direction of the future under building a more lethal force and the modernization of key capabilities; three of which have significant impacts on logistics and sustainment.

The first is the focus on "advanced autonomous systems."[7] As stated in the NDS, "the Department will invest broadly in military application of autonomy, artificial intelligence, and machine learning, including rapid application of commercial breakthroughs, to gain competitive advantages."[8] While it is accepted that unmanned and autonomous systems will be involved in warfighting concepts (some of which is already occurring), the depth and breadth of such application would be significantly expanded in a future concept of operations. Furthermore, the utilization of advanced unmanned and autonomous systems will affect the way and means the naval force provides sustainment and logistics.

The next is "forward force maneuver and posture resilience."[9] The NDS states that "investments will prioritize ground, air, sea, and space forces that can deploy, survive, operate, maneuver, and regenerate in all domains while under attack."[10] The ability for pro-longed sustainment, regeneration, and replenishment will be crucial for U.S. forces to continue operations in combat. Furthermore, it discusses a transition from "large, centralized, unhardened infrastructure to smaller, dispersed, resilient, adaptive basing that include active and passive defenses will also be prioritized."[11] As such, traditional methods of sustainment and logistics may no longer be viable in the future war fighting scenario.

---

[6] Ibid., 3.
[7] Ibid., 7.
[8] Ibid., 7.
[9] Ibid., 6.
[10] Ibid., 6.
[11] Ibid., 6.

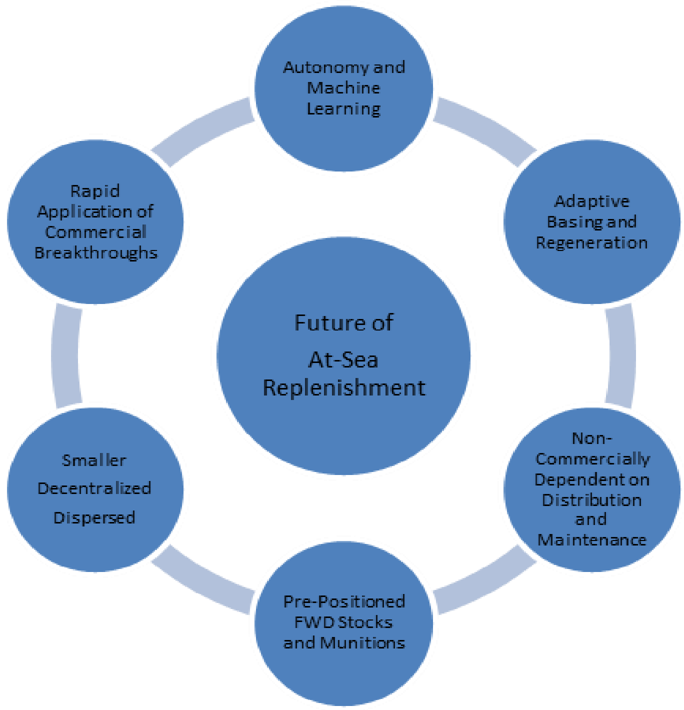
Additionally, the concept of adaptive basing that is smaller and dispersed further emphasizes the need for evolving sustainment and underway replenishment concepts.

The third focus area is "resilient and agile logistics."[12] For reasons already addressed, U.S. naval forces will no longer be able to depend on uncontested environments where the supply chain and logistics pipelines that feed into underway replenishment operations are guaranteed and automatic. As stated in the NDS, "investments will prioritize prepositioned forward stocks and munitions, strategic mobility assets, partner and allied support, as well as non-commercially dependent distributed logistics and maintenance to ensure logistics sustainment while under persistent multi-domain attack."[13] The nature of our pre-positioned stocks will need to evolve, as will our dependency on commercial maintenance and logistics.

The supply chain and logistics mechanisms needed to respond to a rapidly changing environment must evolve from current practices and standard operating procedures. To extend combat capability at sea and decrease supply chain timelines, increased sustainment and afloat repair and consumable inventories will be needed. This will become more crucial in the Pacific area of operation due to the tyranny of distance and contested sea lines of communication. Utilizing strategic guidance and verbiage directly from the NDS, the foundational concepts for the future of replenishment at sea start to take place. These include a focus on "autonomy and machine learning," "adaptive basing and regeneration," "non-commercially dependent on distribution and maintenance," "pre-positioned forward stocks and munitions," "smaller/decentralized/dispersed," and "rapid application of commercial breakthroughs."[14] These concepts formulate the possibilities of future underway

[12] Ibid., 7.
[13] Ibid., 7.
[14] Ibid., 6-7.

replenishment concepts. Current and improving technologies offer promising future logistics capabilities and will be discussed in the next section.



Undersea Basing

Background: While the concept of future undersea basing may initially appear unrealistic or more appropriate for science fiction, efforts for undersea study, habitats, and facilities can be traced back more than sixty years. In 1957, U.S. Navy Commander George F. Bond, a medical officer also known as "Papa Topside" worked on the program *Project Genesis* at the Submarine Medical Research Laboratory.[15] Project Genesis's research focused saturation diving and analyzing the effects of deep sea diving on the human body, including psychological and physiological impacts.[16] These research efforts and findings paved the

[15] John Murray, "Papa Topside, Captain George F. Bond, MC, USN," Faceplate, vol. 9, no. 1, (February 2005): 8-9.
[16] Office of Naval Research, SEALAB Manned Undersea Habitat, accessed on March 1, 2018, https://www.onr.navy.mil/en/About-ONR/History/tales-of-discovery/sealab

way for the concepts and development of the first underwater laboratories and habitats for humans.[17]

For example, in 1962 Captain Jacques-Yves Cousteau's team developed the CONSHELF I (Continental Shelf Station), which housed two individuals (Albert Falco and Claude Wesly) for one week at a depth of 10 meters (32.8 feet).[18] Subsequent projects included CONSHELF II in 1963 where five individuals lived undersea for a month at a depth of 10 meters, while two of the individuals spent a week in the "deep station" section which was at a depth of 15 meters (49.2 feet).[19] Additionally, in 1965 the CONSHELF III accommodated six individuals at a depth of 100 meters (328.1 feet).[20] Cousteau's CONSHELF experiments were successful in proving that within certain parameters, humans could live and work in an undersea environment.

From 1964 to 1969, the U.S Navy was also developing and testing undersea habitats with their Sealab program.[21] In 1964 the U.S. Navy and Office of Naval Research began Sealab I, and despite a minimal budget of $200K, successfully housed four divers at a depth of 193 feet and approximately seven atmospheres of pressure.[22] The successful execution of Sealab I led to Sealab II in 1965.[23] Partnering with the University of California San Diego's Scripps Institution of Oceanography, Sealab II, also known as the "Tiltin' Hilton" due to the uneven placement on the ocean floor, consisted of three teams (each of which would spend

---

[17] Claudio Paschoa, A Short History of Underwater Labs, Marine Technology News, (June 18, 2014), accessed March 1, 2018, https://www.marinetechnologynews.com/blogs/short-history-of-underwater-labs-700486
[18] Cousteau Organization, Conshelf I, II & III, accessed March 1, 2018, https://www.cousteau.org/english/precontinent-i--ii-et-iii.php
[19] Ibid.
[20] Ibid.
[21] Don Walsh, *One Little House Remains on the Bottom of the Sea*, Vol. 128, Annapolis: United States Naval Institute, 2002.
[22] Ben Hellwarth, Sealab: America's Forgotten Quest to Live and Work on the Ocean Floor, 1st Simon & Schuster hardcover ed., New York: Simon & Schuster, 2012, 109.
[23] Ibid., 124.

15 days undersea) at a depth of 205 feet.[24] After another successful execution, planning began for Sealab III which had a minimum depth goal of 430 feet but was later increased to 600 feet.[25] Unfortunately, in 1969 before Sealab III would be fully operational, diver Berry L. Cannon died during repair efforts, likely from carbon dioxide poisoning.[26] As a result, the Navy's Sealab program was cancelled in 1970.[27]

In total, from 1967 to the present day and through such organizations as the National Undersea Research Program (NURP) of the National Oceanic and Atmospheric Administration (NOAA), 67 undersea habitat and research facilities and systems, such as Hydrolab, La Chalupa, and the German Helgoland II system, have been developed and implemented globally.[28] However, there is currently only one remaining habitat that is operational which will be discussed more below.[29]

Current Application: While undersea habitat technologies are being utilized in the hotel and restaurant industry, such as facilities in The Palm Atlantis in Dubai, Ithaa Undersea Restaurant at Conrad Maldives Rangali Island in the Maldives, or the Resort World Sentosa in Singapore, there is currently only one known operational undersea habitat/research facility in the world.[30] The Aquarius underwater laboratory, operated by Florida International University since 2014, was developed to replace Hydrolab and has been operational for 25 years.[31] The Aquarius Reef Base consists three main parts, including a life support buoy, a

---

[24] Ibid., 124.
[25] Ibid., 170.
[26] Ibid., 195.
[27] Ibid., 199.
[28] Don Walsh, *One Little House Remains on the Bottom of the Sea*, Vol. 128, Annapolis: United States Naval Institute, 2002.
[29] Ibid., 2.
[30] Conde Nast Traveler, accessed January 14, 2018, https://www.cntraveler.com/galleries/2016-07-09/11-coolest-underwater-hotels-in-the-world/3
[31] Florida International University, Medina Aquarius Program, accessed March 1 2018, https://aquarius.fiu.edu/

habitat space, and a stable base plate that the habitat is mounted on.[32] The habitat provides 400 square feet of living and work space and has a galley, laboratory, and berthing compartments for up to six researchers.[33] Aquarius researchers normally spend up to two weeks in the habitat, which operates at a depth of 63 feet from the surface.[34] Furthermore, the Aquarius has five main mission areas, including scientific research, training (including with NASA and the U.S. Navy), research and development of undersea technology, ocean education and outreach, and coral reef and ocean observation.[35]

Looking ahead, further technological advances are needed to ensure a sufficient life support system before an undersea basing concept could be realized. This can be extended to both manned and unmanned undersea basing. The concept of undersea fueling stations was recently discussed in reference to a project Teledyne Technologies is currently working on.[36] The concept, which it is said that the U.S. Navy has interest in, is undersea power stations to enable undersea drones to refuel their power cells.[37] While an undersea power station does not specifically align with the concept if undersea basing, it does provide an example of logistics capabilities in the undersea domain given current technologies and the potential they present.

A significant investment would have to be made to explore the potentials due the difficulty for humans operating in deep ocean environments, which has proved to be more complex than space exploration. Yet with emerging technological advances, and the

---

[32] Ibid.
[33] Ibid.
[34] Ibid.
[35] Ibid.
[36] David Axe, *The US Navy Wants Undersea Gas Stations for Underwater Drones*, Motherboard, VICE, accessed May 2, 2018, https://motherboard.vice.com/en_us/article/qvxmv3/the-us-navy-wants-undersea-gas-stations-for-underwater-drones
[37] Ibid.

potential that undersea basing may provide in warfighting, as well as adaptive basing, pre-positioned stocks, and sustainment, it could be worth the investment.

<u>Unmanned Undersea Vehicles – The Echo Voyager</u>

Background: Boeing's Echo Voyager is an Extra Large Unmanned Undersea Vehicle (XLUUV) that offers current multi-mission capability and the potential for future logistics applicability. The Echo Voyager concept was funded and approved in May of 2012, with the subsequent concept of operations finalized in 2013.[38] In March of 2016 Boeing completed construction, and in February 2017 its developmental testing /shore testing was completed.[39] Finally, in June 2017 the Echo Voyager's developmental testing-operational testing/sea trials were completed.[40] Full operational testing and evaluation is currently stated as in progress, as well as both deep depth and endurance testing.[41] Furthermore, in June of 2017, it was announced that the company was teaming up with Huntington Ingalls for undersea drone production.[42]

Current specifications include a maximum depth of 11,000 feet, a maximum speed of 8.0 knots, and a range between recharges of approximately 150 nautical miles at an optimal speed of 2.5 knots.[43] Additionally, this platform can operate for months at a time, has a 6,500 nautical mile fuel module range, can moor to the seafloor and has obstacle avoidance

---

[38] Boeing Company, Echo Voyager Project XLUUV Brief, Boeing Proprietary, Releasable to U.S. Government Personnel Only-Business Sensitive, Presentation for Naval War College, Don Randall, September 26, 2017.
[39] Ibid., 4.
[40] Ibid.
[41] Ibid.
[42] Marcus Weisgerber, accessed March 3, 2018, http://www.defenseone.com/business/2017/06/boeing-shipbuilder-team-build-giant-underwater-drones/138524/
[43] Boeing Company Echo Voyager Product Sheet, accessed Marh 3, 2018, http://www.boeing.com/resources/boeingdotcom/defense/autonomous-systems/echo-voyager/echo_voyager_product_sheet.pdf

capability through its's forward looking sonar (FLS).[44] The 51 foot Echo Voyager is currently designed to be host ship independent, meaning it can operate without the need for a support vessel.[45] Additionally, this platform is designed to be scalable, with scalable payload extensions. In addition to the 51 foot model, there is currently a 65 foot version which includes a "standard" 14' x 8.5' internal payload capacity, as well as an 81-85 foot version that has the capacity for two standard payloads, which is 30' x 8.5'.[46] Furthermore, the 81-85 foot version can house a larger "extended" single payload bay which extends to 34 feet.[47]

Current Application: Currently, the XLUUV has seven primary capabilities in its mission portfolio. These include "surface operations," "deployable payloads," "ASW and maritime patrol," "subsea sample and survey," "subsea work," "target services and training," and "special."[48] Each mission area has its own respective "standard" payload carriage, which can be resupplied or reconfigured at a pier side location.[49] While this mission portfolio is primarily warfare centric, Echo Voyager XLUUV provides an opportunity to explore potential applications for logistics and at-sea replenishment.

The "standard" payload module for Echo Voyager provides approximately 1000 cubic feet (internal volume) and approximately 20,000 pound weigh capacity.[50] As discussed above, the modules are scalable to increase potential payload capacity. Furthermore, the module "conforms to vehicle outer mold line (OML)" and are "hosted inside individual

---

[44] Ibid.
[45] Ibid.
[46] Boeing Company, Echo Voyager Project XLUUV Brief, Boeing Proprietary, Releasable to U.S. Government Personnel Only-Business Sensitive, Presentation for Naval War College, Don Randall, September 26, 2017.
[47] Ibid., slide 14.
[48] Ibid., slide 13.
[49] Ibid., slide 13.
[50] Ibid., slide 12.

pressure vessels or customer provided water-tight containment."[51] Essentially, these features were designed and developed to facilitate logistics capabilities. As stated in their brief, Boeing specifically addresses the Echo Voyager's logistics design under their value proposition by highlighting that the modular payloads, and the platform itself, are able to be transported across multiple transportation methods such as air, sea, land, and railway.[52] Additionally, existing common pier and port facilities can be utilized to transfer the payload carriages.[53]

In discussions with a Boeing Echo Voyager representative, some of the current challenges to consider with analyzing the potential of this platform include commercial satellite utilization and the potential for communications to be unavailable, and the management of payload assignment and prioritization. Furthermore, in the event that the Echo Voyager is stationary, a sensor or alarm indicator would need to be functional in order to detect and communicate a disturbance, as well as be able to distinguish between intentional and unintentional contact.

When considering the applicability of the XLUUV for logistics and assessing its potential with strategic guidance and how the concept of underway replenishment must evolve, the potential for synthesis is significant. Boeing lists specific multi-mission attributes that the Echo Voyager provides, including payloads that enable "interoperability " and "adaptability", "persistence" and "autonomy", "minimize impact to existing infrastructure", and "scalability."[54] These force multiplier attributes can extend to logistics and sustainment

[51] Ibid., slide 12.
[52] Ibid., slide 5.
[53] Ibid., slide 5.
[54] Ibid., slide 30.

and offer potential solutions to the challenges in future operations and the ability to execute "agile logistics" and future underway replenishment concepts.

Autonomous Shipping – Rolls-Royce

"Autonomous shipping is the future of the maritime industry. As disruptive as the smart phone, the smart ship will revolutionize the landscape of ship design and operations." - Mikael Makinen, President Rolls-Royce Marine[55]

Background: The field of autonomous marine platforms continues to develop rapidly. Despite concerns and legal considerations, the Navy continues their interest in developing this technology as a force multiplier and warfighter. Recently, the Office of Naval Research received the autonomous unmanned Sea Hunter prototype platform from DARPA.[56] While the Sea Hunter is currently testing anti-submarine and mine countermeasure capabilities, the technology and autonomous concepts can extend to potential logistics and sustainment mission sets. This can be utilized to support smaller, dispersed, and decentralize operations, or extend to larger cargo platforms such as the autonomous shipping concepts being developed. One such concept and company, is Rolls-Royce.

Current Application: Rolls-Royce is currently an industry leader in the development of autonomous shipping. While many of their concepts include large industrial container ships for global commerce and trade, they are also exploring smaller designs for military utilization. In September 2017, Rolls-Royce announced plans for an autonomous single-mission naval ship. Rolls-Royce General Manager Naval Electrics, Automation and Control, Benjamin Thorp stated "Rolls-Royce is seeing interest from major navies in autonomous, rather than remote controlled, ships. Such ships offer a way to deliver increased operational

---

[55] Rolls-Royce, Ship Intelligence Marine, Autonomous Ships: The Next Step, http://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/customers/marine/ship-intel/rr-ship-intel-aawa-8pg.pdf
[56] Defense Advanced Research Projects Agency, ACTUV "Sea Hunter" Prototype Transitions to Office of Naval Research for Further Development, accessed May 10, 2018, https://www.darpa.mil/news-events/2018-01-30a

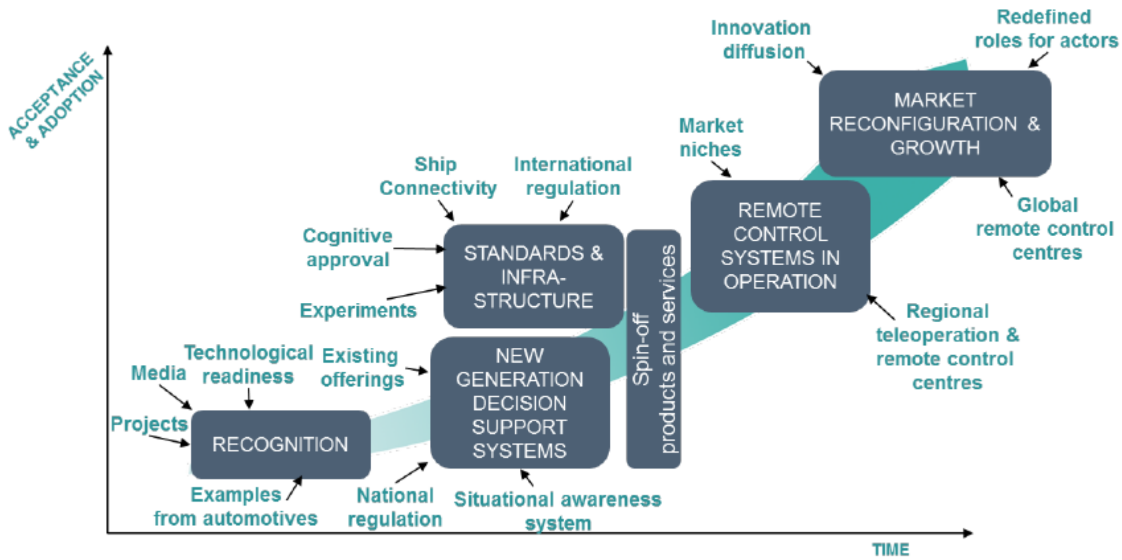
capability, reduce the risk to crew and cut both operating and build costs."[57] Furthermore, he stated that "over the next 10 years or so, Rolls-Royce expects to see the introduction of medium sized unmanned platforms, particularly in leading navies, as the concept of mixed manned and unmanned fleets develops."[58]

According to a Rolls-Royce Advanced Autonomous Waterborne Applications Initiative (AAWA) white paper, there are four anticipated stages of transition for autonomous shipping.[59] While this is targeting for commercial and private sector maritime shipping, it provides a useful framework to base transitional concerns that might be held by the Navy. The first is the recognition and acceptance of the potential and possibilities that autonomous shipping could provide.[60] As discussed above, the energy behind such projects as the Sea Hunter is a positive step in this recognition, even if current mission sets are finite. The next transition phase is incremental adoption and utilization of a single ship or platform, which likely would not be a fully autonomous platform.[61] This concept, especially in the context of usage in the Navy for underway replenishment platforms, would potentially include minimally manned crews, or the concepts of "human in the loop" or "human on the loop." The third phase identified in the white paper is a shift in focus beyond a single ship into multiple ship operations and traffic management.[62] Furthermore, this phase includes developed support infrastructure, the standardization of procedures and international

---

[57] Rolls-Royce, accessed March 5, 2018. https://www.rolls-royce.com/media/press-releases/yr-2017/12-09-2017-rr-reveals-plans-for-autonomous-naval-vessel.aspx
[58] Ibid.
[59] Jouni Saarni, Sini Nodberg-Davies, Hannu Makkonen, Rolls-Royce Ship Intelligence Marine, Advanced Autonomous Waterborne Applications Initiative (AAWA), *Remote and Autonomous Ships: The Next Steps,* 2016, pg: 83-85, http://www.rolls-royce.com/products-and-services/marine/ship-intelligence.aspx#section-overview1.
[60] Ibid., 83.
[61] Ibid., 84.
[62] Ibid., 84.

regulations, and "ship connectivity based on satellite and shore-based communications are to be gradually enlarged to support the autonomous traffic."[63] The fourth and final phase is the transition into a "global scale" where mass acceptance and utilization is experienced.[64] In other words, concepts of autonomous shipping will be regularly identified as the standard way of operating and doing business. Rolls-Royce's timeline currently estimates a reduced crew with remote support by 2020, a remote controlled unmanned blue water vessel by 2030, and a fully autonomous unmanned blue water vessel by 2035.[65]



Source: "Transition Roadmap to Autonomous Shipping, Jouni Saarni, Sini Nodberg-Davies, Hannu Makkonen, Rolls-Royce Ship Intelligence Marine, Advanced Autonomous Waterborne Applications Initiative (AAWA), *Remote and Autonomous Ships: The Next Steps*, 2016, pg: 88.

We currently see autonomous shipping transitioning through such phases. In addition to projects on the military side such as Sea Hunter, we also can see the progress on the commercial side. Recently it was announced that the world's first autonomous shipping company had been established. Massterly, a Norwegian joint venture, is schedule to be

[63] Ibid., 84.
[64] Ibid., 85.
[65] Rolls-Royce Info Sheet, accessed March 5, 2018, http://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/customers/marine/ship-intel/rr-ship-intel-aawa-8pg.pdf.

operational by August of 2018.[66] According to a Marine Link article, Thomas Wilhelmsen, CEO of the Wilhelmsen group stated "Through the creation of the new company named Massterly, we take the next step on this journey by establishing infrastructure and services to design and operate vessels, as well as advanced logistics solutions associated with maritime autonomous operations."[67] As trust, comfortability, and confidence continues to increase, so too will the application and normalization of autonomous shipping technology.

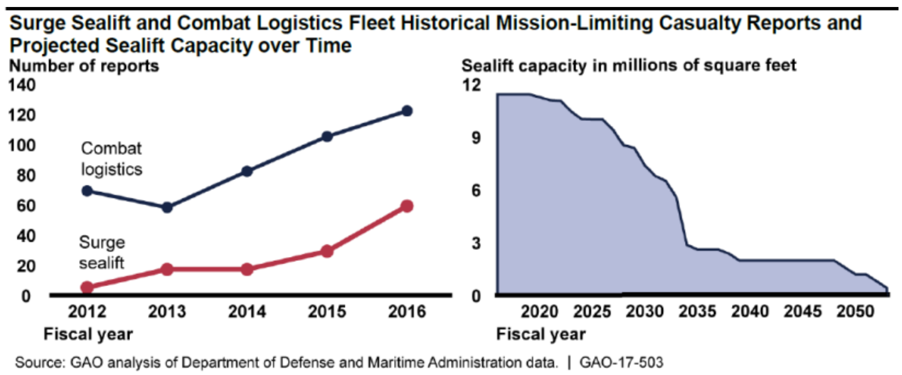
While the concept of autonomous shipping may provide possible solutions and agility to underway replenishment concepts, it also offers potential to current challenges facing the Military Sealift Command (MSC). According to Paul Jaenichen Sr., the head of the U.S. Maritime Administration (MARAD), the U.S. will need 70,000 new personnel by 2022 in order maintain the maritime fleet.[68] Furthermore, only 900 personnel graduate per year from the Merchant Marine Academy, as well as the six additional state maritime academies.[69] This is resulting in the substantial shortage of qualified personnel to man and operate the maritime fleet. In addition to a shortage of mariners, the readiness of the MSC fleet is currently under scrutiny.

A 2017 GAO report submitted to congressional committees provided some concerning findings. Regarding the surge sealift and combat logistics fleet, the report concluded that over that past five years, there is a downward trend in operational readiness and availability, and increasing trends in overschedule maintenance periods and mission-

---

[66] Greg Trauthwein, World's First Autonomous Shipping Company Formed, *Marine Link*, April 4, 2018, accessed April 20, 2018, https://www.marinelink.com/news/autonomous-shipping435906
[67] Ibid.
[68] John Grady, U.S. Facing Looming Shortage of Merchant Mariners, USNI News, accessed March 10, 2018, https://news.usni.org/2016/03/22/u-s-facing-looming-shortage-of-merchant-mariners
[69] Ibid.

limiting equipment casualties.[70] Surge sealift is an issue as well. According to the same GAO report, the average age of surge sealift fleet is 40 years old.[71] Furthermore, it is estimated that sealift capacity will decline by 25% over the next decade due to ships in the surge fleet reaching the end of their service lives.[72]



As discussed above, part of strategic guidance and foundational aspects of future underway replenishment concepts includes being smaller, decentralized, and dispersed. This poses yet another challenge. The report further stated that "according to Navy and MSC officials, a greater reliance on distributed operations and the lethality provided by a widely distributed fleet will require resupplying ships that are farther apart and generally increase the demand on the combat logistics force;" however, "the Navy has not assessed the potential effects of dispersed operations on the Combat Logistics Force."[73] These challenges are significant considering approximately 90% of U.S. military supplies and equipment is provided by MSC via sealift.[74] Furthermore, there has been a consistent declined in overall U.S. Merchant Marine capacity. In 1951, the U.S. Merchant Marine consisted of 1,288

---

[70] United States, Government Accountability Office, Navy Readiness, Actions Needed to Maintain Viable Surge Sealift and Combat Logistics Fleets: Report to Congressional Committees, Washington, D.C.: United States Government Accountability Office, 2017, 11-16.
[71] Ibid., Report Cover Sheet Summary.
[72] Ibid.
[73] Ibid., 22.
[74] Ibid., 1.

international trading ships.[75] Currently, the number of vessels has decreased to only 81, negatively impacting the military's ability to leverage the Merchant Marine fleet for large scale and sustained shipping operations for overseas conflicts.[76] According to the commander of USTRANSCOM, General Darren W. McDew, in statements to a Senate panel, "If the fleet continues to lose ships, a lengthy, mass deployment on the scale of Desert Shield/Desert Storm could eventually require U.S. forces to rely on foreign-flagged ships for sustainment."[77] With deceasing numbers in available and qualified mariners, an aging fleet with declining capacity, the potential shortage of CLF and merchant shipping, and the challenge of future operations being more dispersed, autonomous shipping platforms could have a significant value-added impact on the future of underway replenishment.

<u>Additive Manufacturing / Three Dimensional Printing</u>

Background: Additive manufacturing, also referred to as three dimensional printing (AM/3DP), is not a new technology. In fact, its origins, patents, and uses go back more than thirty years.[78] According to Terry Wohlers, the principal consultant and president of Wohlers Associates Inc. and principal author of the annual Wohlers Report, "the ISO/ASTM 52900 standard defines additive manufacturing (AM) as the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive and formative manufacturing methodologies."[79] Currently, there are seven broadly recognized AM/3DP technologies utilized throughout government and industry. These include binder

---

[75] Tim Johnson, "The US Merchant Marine Fleet Is Dying — And It May Hurt America's Ability To Wage War Abroad," McClatchy Washington Bureau, Task and Purpose, accessed on May 15, 2018, https://taskandpurpose.com/us-mercant-marine-fleet-military/.
[76] Ibid.
[77] Ibid.
[78] Richard Shea, Nicole Santos, and Robert Appleton, "Additive Manufacturing in the DoD." (2015): 1-31, http://www.iceaaonline.com/ready/wp-content/uploads/2016/06/BC05-paper-3D-Printing-DOD.pdf.
[79] Terry Wohlers, "Additive Manufacturing and Composites: An Update," Composites World 3, no. 6 (06, 2017): 6.

jetting, material jetting, powder bed infusion, directed energy deposition, sheet lamination, vat photopolymerization, and material extrusion.[80] Brief descriptions of these technologies can be seen in the table below.

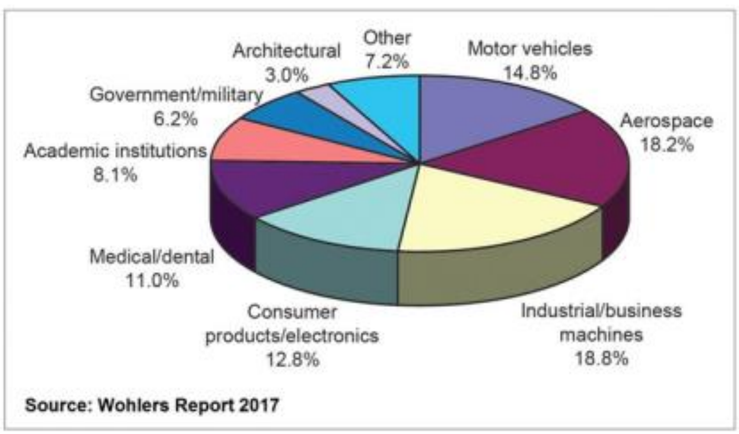
Technology	Description
Binder Jetting	Liquid bonding agent selectively deposited to join powder
Material Jetting	Droplets of build material selectively deposited
Powder Bed Fusion	Thermal energy selectively fuse regions of powder bed
Directed Energy Deposition	Focused thermal energy melts materials as deposited
Sheet Lamination	Sheet of material bonded together
Vat Photopolymerization	Liquid photopolymer selectively cured by activation
Material Extrusion	Material selectively dispensed through a nozzle or orifice

Source: Summary of the 7 Recognized Technologies, Richard Shea, Nicole Santos, and Robert Appleton. "Additive Manufacturing in the DoD." (2015). 7

While in its early days AM/3DP was utilized primarily for cost effective prototyping, it continues to emerge as a technology with significant potential for both industry and the Department of Defense (DoD). Professor John Hart, an Associate Professor of Mechanical Engineering and leader of the Mechanosynthesis Group at the Massachusetts Institute of Technology (MIT), states that there are several reasons why it is believed AM/3DP will continue to grow in capability, capacity, and utilization. These include the increase in available software programs for computer-aided design and computer-aided manufacturing (CAD/CAM), improvements in component and automation technologies, patent expiration, and an increasing library of possible printable materials.[81] Furthermore, growth is expected

[80] Richard Shea, Nicole Santos, and Robert Appleton. "Additive Manufacturing in the DoD." (2015): 7, http://www.iceaaonline.com/ready/wp-content/uploads/2016/06/BC05-paper-3D-Printing-DOD.pdf.
[81] John Hart, Additive Manufacturing, MIT 2.008x, Lecture Slides, (November 2016), accessed February 20, 2018, https://www.slideshare.net/AJohnHart/additive-manufacturing-2008x-lecture-slides.

to continue due to significant investment by private industry and government, and perhaps most important as Professor Hart states, is "momentum, confidence, and creative vision."[82] Data supports this continued industry growth trend as well. According to Wohlers, the additive manufacturing industry grew by 17.4% (Compound Annual Growth Rate or CAGR) in 2016 to an estimated $6.063 billion.[83] Additionally, the CAGR from 2013-2016 was 28%, and if extended back over the past 28 years, grew by 25.9%.[84] While $6 billion may not seem significant when compared to other industries, Wohler points out that these revenue estimates are not inclusive of research and development initiatives.[85] Furthermore, part production from surveyed additive manufacturing companies comprised of 60.6% of their respective businesses, compared to 15.6% in 2008.[86] The below table is an illustration of additive manufacturing part utilization in various industries as of 2016.



Source: Additive Manufacturing Utilization in Industry, Cadalyst Staff http://www.cadalyst.com/hardware/3d-printers/wohlers-report-finds-slower-overall-growth-more-competition-3d-printing-space-3, accessed February 20, 2018.

Despite this growth, there are still several challenges in regards to AM/3DP. According to Hart, speed or rate and quality remain relatively low, while cost (relative to

[82] Ibid., 8.
[83] Terry Wohlers, "Additive Manufacturing and Composites: An Update," Composites World 3, no. 6 (06, 2017): 6.
[84] Ibid., 6.
[85] Ibid., 6.
[86] Ibid., 6.

process or material) can be expensive as compared to more traditional manufacturing methods.[87] Trust and confidence in materials and process are also factors within the calculus of AM/3DP utilization, especially within the DoD. However, Hart states that although these challenges and limitations exist, the potential for AM/3DP technology are significant. Justifications include rapid prototyping, the ability to create complex geometries, and the ability to create multiple and new materials.[88] Furthermore, the utilization of AM/3DP facilitates the potential for enhanced performance, the ability for personalized or specialized low-volume manufacturing, and enables flexibility.[89]

In looking at AM/3DP's challenges and opportunities, perhaps most intriguing, in regards to U.S. naval forces logistics and sustainability, is the flexibility and personalized manufacturing. In a 2014 study and report conducted by Deloitte regarding AM/3DP opportunities within the DoD, one of their focus areas was on the supply chain value and the ability to deliver "the right part" at the "right place" and "right time" in the "right quantity."[90] As stated in the Deloitte report, AM/3DP can increase the value to the end user due to enabling manufactured parts that are "individually customized for specific purposes," "produced at its actual point of use," "created on demand," and "manufactured in lower quantities with no loss in design fidelity."[91] These enablers are critical capabilities for underway operations and sustainment. As described by Hart, what AM/3DP offers the end

---

[87] John Hart, Additive Manufacturing, MIT 2.008x, Lecture Slides, (November 2016), accessed February 20, 2018, https://www.slideshare.net/AJohnHart/additive-manufacturing-2008x-lecture-slides, 17.
[88] Ibid., 13.
[89] Ibid.
[90] M. J. Louis, T. Seymour, and J. Joyce, "3D opportunity for the Department of Defense: Additive manufacturing fires up (A Deloitte series on additive manufacturing)," (2014). 1-28.
[91] Ibid., 11.

user is the ability to manufacture complex and customized parts without the need for industrial volume or quantities.[92] This is further illustrated in Figure 3 shown below.

Source: The Supply Chain Value Envelope. M. J. Louis, T. Seymour, and J. Joyce, "3D opportunity for the Department of Defense: Additive manufacturing fires up (A Deloitte series on additive manufacturing)," (2014). 11

Current Application: The acceptance of the potential of AM/3DP has been supported by senior leadership within the DoD. For example, in September of 2015, former Secretary of the Navy Ray Mabus issued a memorandum to the Chief of Naval Operations, Commandant of the Marine Corps, and the Assistant Secretary of the Navy (Research, Development and Acquisition) directing the development and implementation plan for AM/3DP.[93] The memorandum gave direction to "increase development and integration of additive manufacturing systems," to "develop the ability to qualify and certify AM parts," to "standardize the digital AM framework and tools and enable end to end process integration,"

---

[92] John Hart, Additive Manufacturing, MIT 2.008x, Lecture Slides, (November 2016), accessed February 20, 2018, https://www.slideshare.net/AJohnHart/additive-manufacturing-2008x-lecture-slides. 20.
[93] United States, Secretary of the Navy, Ray Mabus, Memorandum for Chief of Naval Operations, Additive Manufacturing/3-D Printing, September 3, 2015.

and to "establish the DON advanced integrated digital manufacturing grid."[94] While AM/3DP is currently being utilized in the fleet (such as on the USS Essex and MCAC Cherry Point), it has not yet reached wide-spread utilization or industrial capacity.[95] However, the Navy has seen successful testing on both smaller and larger scales.

For example, NAVAIR has established innovation cells and fabrication labs throughout its organization to familiarize its workforce with AM/3DP technology.[96] Their efforts resulted in the production of an H-1 helmet visor clip via three dimensional printing that was the first additive manufacturing part approved for fleet utilization and operations in the Navy supply system.[97] Furthermore, a project known as 3-D Sailor is looking to expand this concept to the production of plastic pieces of flight deck gear, such as float coat clips and cranial helmet front panels, as well as developing digital technical data packages (TDPs) for the respective parts.[98] NAVIR has also successfully produced a link and fitting for the MV-22B Osprey's engine nacelle which was subsequently tested and flown in the aircraft.[99]

More recently, the Navy, in collaboration with Oak Ridge National Laboratory (ORNL), Carderock Division's Disruptive Technology Lab, and the Naval Surface Warfare Center, produced a submarine hull, known as the Optionally Manned Technology Demonstrator (OMTD).[100] The 30 foot concept hull is currently the Navy's biggest three

---

94 Ibid.

95 United States, Secretary of the Navy, Ray Mabus, Memorandum for Chief of Naval Operations, Additive Manufacturing/3-D Printing, September 3, 2015.

96 Jeff Newman, "Hitting Print: Navy On Board with Additive Manufacturing," Naval Aviation News, accessed on February 23, 2018, http://navalaviationnews.navylive.dodlive.mil/2017/06/08/hitting-print-navy-on-board-with-additive-manufacturing/

97 Ibid.

98 Ibid.

99 Ibid.

100 Sarah Saunders, "US Navy and ORNL Team Up to Develop the Military's First 3D Printed Submarine Hull on the BAAM," 3DPrint.Com, accessed on February 23, 2018, https://3dprint.com/181795/navy-ornl-3d-printed-sub-hull/.

dimensionally printed asset and was based on the submersible SEAL Delivery Vehicle (SDV).[101] Their efforts not only reduced production time, but also reduced production costs by approximately 90%.[102] Furthermore, according to a 2017 Business Insider report, fleet-ready OMTD prototypes could be operational by 2019.[103] In contrast to new concepts, AM/3DP can assist with an issue that is unfortunately prevalent throughout the DoD, which is the obsolescence of parts. Due to the extended service life of platforms, equipment and weapons systems, many component parts are no longer readily available of even manufactured. Deloitte refers to two examples, such as the Air Force B-52 and the Navy's J-6000 Tactical Support System Servers on Los Angeles and Ohio-class submarines, both of which utilize parts that are no longer produced by the initial manufacturer.[104] AM/3DP offers the potential to "overcome obsolescence" and to ensure on-demand parts despite the reality that they are no longer being manufactured.[105]

While not at the industrial level, these examples illustrate the current utilization, flexibility, and potential of AM/3DP. However, challenges remain in fully implementing AM/3DP as a primary and consistent source of part production in the DoD. According to Deloitte's report, five key challenges face the DoD in regards to developing and implementing a digital supply chain that would facilitate wide-spread utilization.[106] These include "parts testing and qualification," "information and communications security,"

---

[101] Ibid.
[102] Ibid.
[103] Jared Keller, "The Navy can now 3D-print submarines on the fly for SEALs," Business Insider, accessed on February 23, 2018, http://www.businessinsider.com/the-navy-can-now-3d-print-submarines-the-fly-seals-2017-7.
[104] M. J. Louis, T. Seymour, and J. Joyce, "3D opportunity for the Department of Defense: Additive manufacturing fires up (A Deloitte series on additive manufacturing)," (2014). 7.
[105] Ibid., 7.
[106] M. J. Louis, T. Seymour, and J. Joyce, "3D opportunity for the Department of Defense: Additive manufacturing fires up (A Deloitte series on additive manufacturing)," (2014). 12.

"training and developing of necessary skillsets," "intellectual property issues," and lastly, "DoD-wide AM governance."[107] Despite the known and unknown challenges, AM/3DP offers potential to support strategic guidance and "agile logistics" concepts discussed above such as regeneration and becoming non-commercially dependent on distribution and maintenance.

A Future Concept of Operations for Underway Replenishment

"The idea of the future being different from the present is so repugnant to our conventional modes of thought and behavior that we, most of us, offer a great resistance to acting on it in practice."
- John Maynard Keynes[108]

As discussed above and in following with strategic guidance, the foundations of future underway replenishment concepts of operations should be inclusive of the themes of "autonomy and machine learning," "adaptive basing and regeneration," "non-commercially dependent on distribution and maintenance," "pre-positioned forward stocks and munitions," "smaller/decentralized/dispersed," and "rapid application of commercial breakthroughs." As such, this concept envisions a combat logistics force and ship platforms being smaller, decentralized, and more dispersed. However, it is acknowledged and should be noted that these concepts do not attempt to account for or solve the challenge of at-sea fuel replenishments.

Assumptions: Looking ahead the author makes certain assumptions regarding technological advances, especially in intelligent agents and autonomous vehicles for the U.S. Navy. Per current trends and the speeds at which advancements and improvements are being realized, quantum computing will have enabled secure data transfer to allow autonomous and

---

[107] Ibid.; 12, 13.
[108] Office of the Director National Intelligence, "Global Trends 2030: Alternative Worlds," A publication of the National Intelligence Council, (2012). https://www.dni.gov/files/documents/GlobalTrends_2030.pdf

unmanned vehicles to operate securely. Maritime law will have adjusted and recognized autonomous military ships and commercial shipping vessels throughout the globe. Additionally, a substantial increase in trust and confidence between humans and intelligent agents will have been achieved. The capabilities of additive manufacturing/three dimensional printing will have advanced significantly, as well as the linkages between industry and weapons systems. Assets, especially on the surface of the ocean, will likely be impossible to hide. This will necessitate a significant increase in undersea operations. Due to the increase in autonomous and unmanned systems, the human role, while not obsolete, will be limited in at-sea operations. As such, while logistics support for humans at sea will decrease, the need for replenishment at sea will remain a necessity. Finally, despite current DoD fiscal limitations, the concepts discussed are not concerned with budget constraints.

Concept of Operations: Looking out more than 30 years into the future and integrating our assumptions and existing technologies, the potential at-sea replenishment capabilities begin to emerge. U.S. global operations in the maritime domain continue, although freedom of navigation is no longer guaranteed. Carrier strike groups no longer operate in traditional deployment methods and are on schedule to be phased out in their traditional form. While still utilized, they operate further behind contested areas of operation due to lack of protection against enemy capabilities. The U.S. now operates a smaller, more dispersed fleet of assets that are decentralized, many of which are either minimally manned or fully autonomous. Mission command has been further integrated allowing faster decision making and flexible operations to adapt to ever changing environments.

Undersea basing has been reinvested in and the Sealab program, restarted through partnerships with private industry, currently operates several facilities. Only a small number of these are manned. The majority of undersea bases are autonomous and are utilized for monitoring, sensing, and fueling/recharge stations for undersea unmanned and autonomous vehicles. Furthermore, these facilities are in keeping with the necessity for adaptive basing and regeneration and are utilized for pre-positioned material. This goes well beyond storage of offensive munition payloads, and is further expanded to repair and sustainment stocks and material; much of which in past decades would have been stored and supplied from traditional warehouses and Military Sealift Command ships. Extra Large Unmanned Undersea Vehicles (XLUUVs) such as the Echo Voyager extends the themes of autonomy and supporting a fleet that is smaller, decentralized, and dispersed. This platform also extends the concepts of pre-positioned forward stocks and munitions, as a fleet of logistics XLUUVs operate as mobile warehouses and pre-positioned material vehicles for parts, stocks of additive manufacturing materials such as metals, polymers, and resins, as well as non-perishable personnel sustainment food stuffs. These can be rotated out easily depending on the threat assessment and mission requirements.

On the surface, autonomous cargo shipping is the standard method of transportation of larger supplies of sustainment material. However, these have been scaled down both in size as well as inventories, as “push logistics” has become the standard operating procedure for underway replenishment. Pre-determined stores loads in quantity and inventory breadth, including subsistence for manned vessels, push their resupply loads in compatible modules instead of previous procedures of awaiting orders and scheduling. Connected replenishment will still be conducted when necessary, but at smaller durations due to pre-determined resupply orders. Furthermore, unmanned and autonomous aerial vehicles deliver more frequently as needed. Similar in concept to pre-positioned ships, unmanned cargo and supply ships can house pre-positioned stocks that are mobile. In order to sustain operations, decreasing the supply chain and reliance on shore-based supply and logistics support will be vital in future operations and combat. As such, autonomous vessels, both undersea and on the surface, provide agility, mobility, and increased time on station in contested environments to enable "posture resilience."

Additive Manufacturing/Three Dimensional Printing (AM/3DP) has evolved to not only having capacity on manned ships to ensure sustainment and regeneration, but also has been fully integrated in autonomous ships, resulting in autonomous AM/3DP vessels. These platforms enable ship operations to be non-commercially dependent on the distribution of parts and maintenance and have significantly reduced consolidated onboard ship allowances and inventories. As such, AM/3DP will enable a significant number of weapons and ship systems to be fully interchangeable and repaired utilizing parts (both repair and consumable) that were three dimensionally printed while at sea for rapid replenishment. Furthermore, the advancements in machine learning and artificial intelligence (AI) have provided predictive analytics that anticipates the wearing down or breakage of equipment and parts.

U.S. Naval combatants are operating in contested environments, many of which are doing so independently. Cargo needed for sustainment via underway replenishment is provided by both autonomous undersea and surface platforms. Once AI identifies the material or parts needed for the anticipated repair, it sends the required data to an AM/3DP platform which manufactures the parts and sends them via an autonomous aerial vehicle, all of which occurs without a human in the loop. Pre-positioned material, located in undersea bases, XLUUVs, and autonomous surface ships rendezvous when needed for determined mission sets; all of which are smaller, decentralized, and dispersed.

<u>Internal and External Threats</u>

"*What I fear is not the enemy's strategy, but our own mistakes" - Pericles*[109]

Internal: It should be noted that regardless of weapons systems and the logistics built to sustain them, current internal challenges pose the largest threat to innovation, technological prowess, and the ability to maintain a comparative advantage over potential adversaries. This section posits that the most pressing internal challenges of future concepts are speed, agility, innovative industry partnerships, and a lack of focused and consolidated effort on future at-sea replenishment concepts.

Regardless of the clarity, direction, and focus of any strategy, the ability to execute is what matters in the end. For the U.S., the speed at which we are able to prepare and support the execution of strategy is severely lagging behind the pace of technological advances and emerging threats. This can be demonstrated in our current acquisition system and process. As discussed in the CNO's May 2017 correspondence *The Future Navy,* China was able to commission 18 ships in 2016.[110] The speed at which China can procure and manufacture both naval and commercial ships outpaces the U.S. While the U.S. is positioned with the industrial base and technological capabilities needed to ensure an executable strategy, the speed at which the process can support execution is inadequate and poses an internal threat to our defense posture and competitive edge. This also affects our logistics solutions and capabilities. A moratorium is needed on current limitations in our acquisition practices to enable capabilities to keep pace with technological advances. Our bureaucratic nature continues to stifle progress and illustrates the need for an acquisition process overhaul.

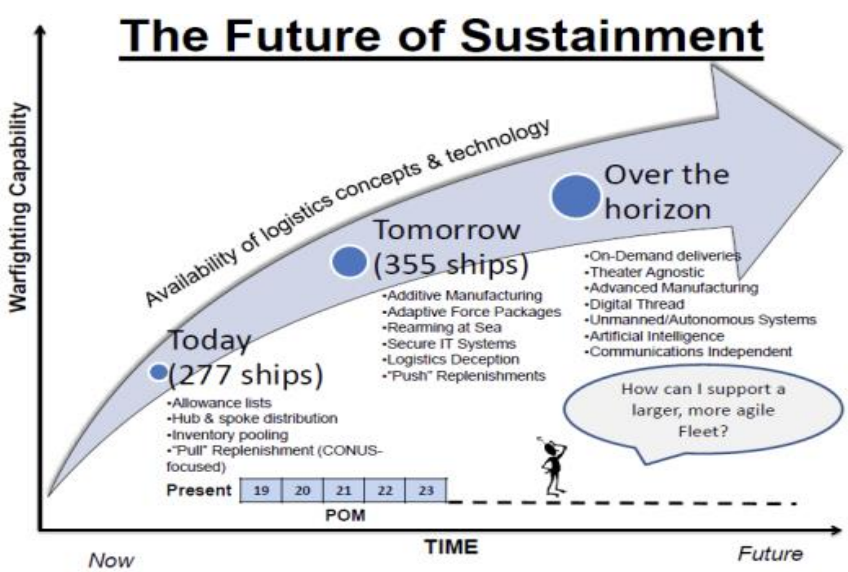
---

[109] Thucydides, Robert B. Strassler, 1937, and Richard Crawley 1840-1893, The Landmark Thucydides: A Comprehensive Guide to the Peloponnesian War, Free Press trade pbk. ed, New York: Free Press, 2008.
[110] John M. Richardson, "The Future Navy," (May 2017), accessed March 3, 2018, http://www.navy.mil/navydata/people/cno/Richardson/Resource/TheFutureNavy.pdf

Agility, like speed, is needed to ensure capabilities keep pace with technology and a growing range of threats. In addition to flexibility in procurement and acquisition policy, agility is required in developing a defense force that can execute the strategy of the future Navy and joint force. For example, the current inability for the Department of Defense (DoD) to recruit specific skillsets and technical backgrounds due to antiquated organizational structures and guidelines is hindering capabilities. Over the past 16 years, value has been proven in interagency cooperation and diversified skillsets outside of military channels. The capability of individuals should outweigh military standards as currently defined, and innovative solutions are needed to employ the right personnel that can meet the technological challenges ahead. No doubt, competitors and adversaries will utilize the resources they have at hand, and the joint force should capitalize on available talent and not be limited to prescribed qualifications that are outdated and ill-suited in the current environment.

Cultivating and sustaining innovative industry partnerships are crucial to the strategic needs of the Navy and joint force. While this remains true for our international partners, the ability to increase partnerships with industry in new ways and develop creative incentives that encourage collaborative innovation will further facilitate accomplishing U.S. strategic goals. Due to the DoD's continued growth in digital dependency, the government and private sector are no longer entities separated by roles, policies, and authorities. In fact, they share increasing equities and risk. Furthermore, the need for innovative partnerships is vital as the DoD is no longer a national leader in research and development efforts. Without such collaborative partnerships, U.S. forces risk falling behind their peer and near-peer competitors.

Finally, the lack of a focused, consolidated effort in exploring future at-sea replenishment and logistics concepts for the Navy presents a significant challenge. Presently, the Navy Supply Corps has a ten person Supply Advisory Team (SAT) looking at future logistics concepts whose mission is "to identify and explore innovative technology, improved processes, and revised policies to transform emerging logistics concepts into scalable, enabling capabilities for the warfighter."[111] The team has identified candidate areas of investigation amongst policy, process, and technology. Policy areas of investigation include overarching strategy and plans, as well as operational concepts. Process areas include organizational redesign, precision allowancing, push or predictive logistics, big data analytics, and digital logistics.[112] Finally, technological areas of investigation include unmanned autonomous logistics system, assured logistics information exchanges, non-standard material positioning, swarms, robotics, artificial intelligence and human-machine teaming, industrial internet of things / telematics, and additive manufacturing.[113]



Source: The Future of Sustainment. (Supply Advisory Team, November 2017).

[111] SAT Future Logistics Concepts Brief 1-13.
[112] Ibid., 12.
[113] Ibid., 12.

Unfortunately there is currently no dedicated office with the primary mission of future underway replenishment concept development or advocacy. The SAT noted the cultural implications of emerging technological changes and warned that a "continued delay in purposeful advocacy and action may jeopardize future progress."[114] While some efforts are ongoing, the issues of resourcing, both in personnel and an operations budget, remain a barrier to progress.

The other Navy-centric logistics entity, the Military Sealift Command (MSC), has recently established the TALUGA Group, which is exploring some advanced technologies and innovation, and possible implementation into concepts of operation for underway replenishment. However, these efforts and concepts are more directed at current and near-future operations and less on technological innovation and alternative methods in at-sea logistics and underway replenishment. The TALUGA Group, like the Supply Corps' SAT, is currently limited in personnel and resources. It is also important to note that the Defense Advanced Research Projects Agency (DARPA) has identified the lack of effort in naval logistics innovation projects and concept development. Despite the efforts discussed above, the lack consolidation or office with authorities to champion future logistics concepts, innovations, and technologies presents a significant threat. Unless an investment is made in resources and personnel, the Navy will run the risk of being unable to innovate and overcome the future challenges of at-sea replenishment in contested environments.

The future Navy and joint force faces an uncertain and increasingly dynamic environment. Threats will continue to increase across all warfare domains, and the ability to operate uncontested is quickly diminishing with the emergence of China. In order for the

[114] Ibid., 9.

U.S. to maintain superiority across all domains, current policy, legislation, and internal processes must be overhauled and reimagined. This involves the speed at which we can acquire capabilities, agility in processes, particularly in recruiting and maintaining specific skillsets and technical backgrounds, and finally, cultivating and sustaining innovative industry partnerships, and a focused and consolidated effort on future logistics and at-sea replenishment concepts. Without these essential strategic needs, U.S. dominance, security, and competitive edge will continue to be marginalized.

External: The Threat of a Rising China[115] So why is it crucial not only to rectify internal challenges, but also to ensure the U.S. maintains a technological comparative advantage over potential adversaries? As discussed above, U.S. naval forces will continue to be challenged in the future, and the biggest threat from a near-peer competitor will come from China. When assessing China's aggregate power, there is cause for concern. Aggregate power includes resources such as population size, industrial and military capability, technological prowess, and economic strength.[116] China is currently the world's most populous country, with an estimated 1.3 billion people and has a labor force that exceeds 800 million.[117] With its population size, China maintains the capability to yield great power from its human capital and can sustain its industrial capacity.

China's industrial capability and capacity is well established and has significant implications. One example is their ability to produce 800 million metric tons of crude steel (50% of global supply), approximately four metric tons of coal, and more than 25% of the

---

[115] The following section was taken from a previously submitted paper by Richard D. Jones to the Faculty of the United States Naval War College Newport, RI in partial satisfaction of the NSDM requirements of the Department of Joint Military Operations titled India's Strategic Crossroad, February 12, 2018.
[116] Stephen M. Walt, *The Origins of Alliances*, (Ithaca: Cornell University Press, 1987).
[117] CIA World Factbook, accessed December 8, 2017, https://www.cia.gov/library/publications/the-world-factbook/geos/in.html.

global supply of vehicles.[118] China has an estimated 62,000 industrial patent applications and is the world's largest producer of ships, speed trains, and infrastructure support such as tunnels, bridges and highways.[119] Furthermore, they supply approximately 50% of global industrial goods and one third of global agricultural products.[120] China is a world leader in gross value of industrial output, including mining and ore processing, armaments, machine building, aircraft, telecommunications equipment, commercial space launch vehicles, and satellites.[121]

Industrial capability enables military growth, and China has experienced a dramatic increase due to defense spending and modernization efforts. Their 2016 defense expenditures were 1.9% of GDP and have continued to increase.[122] Between 2007 and 2016, China's defense budget averaged an 8.5% annual increase, and as of March 2016 they stated they would increase their defense budget by another 7% to $143.3 billion USD.[123] China is second only to the U.S. in defense spending, and can sustain increased defense budgets well into the future.[124] For example, they continue to modernize capabilities in anti-access/area denial, long range precision strike ballistic missile defense, and both surface and undersea operations.[125] Furthermore, China aims to modernize across all domains as they develop capabilities in space and counter-space, information operations, and cyber-attack

---

[118] Wen Yi, "The Making of an Economic Superpower ―Unlocking China's Secret of Rapid Industrialization," Research Division Federal Reserve Bank of St. Louis Working Paper Series, Working Paper 2015-006B (June 2015): 1-180.
[119] Ibid., 4.
[120] Ibid., 4.
[121] CIA World Factbook, accessed December 8, 2017, https://www.cia.gov/library/publications/the-world-factbook/geos/in.html.
[122] Ibid. Likely the official figures, which are thought to be an underestimate of actual spending.
[123] United States, Department of Defense, Office of the Secretary of Defense and United States, Department of Defense, "Military and Security Developments Involving the People's Republic of China: A Report to Congress Pursuant to the National Defense Authorization Act for Fiscal Year," *Military and Security Developments Involving the People's Republic of China*, (May 15, 2017): 1-106.
[124] Ibid., 65.
[125] Ibid., 49, 50.

operations.[126] The increase in defense spending and modernization has also resulted in an increase in the military's global reach. China has begun construction on its military base in Djibouti and continues efforts for additional foreign port access to support global deployments in countries such as Sri Lanka and Pakistan.[127]

Although China has established itself as the leader in industrial capacity in manufacturing, it also has aspirations to become the global leader in information and communications technology. China's technological prowess has been aggressive as it seeks to dominate advanced technology markets, which deeply impacts their military and economic strength and capability. Government promulgation and directives such as the National Medium and Long-term Program for Science and Technology Development (2006-2020) was a strategy that directed the country to master 402 core technologies and obtain an absolute economic advantage throughout all advanced technology industries, including aviation and aerospace, semiconductors, and pharmaceuticals.[128] This directive marks a significant goal, as the Chinese aim to surpass all global competitors. According to testimony before the House Committee on Foreign Affairs Subcommittee on Asia and the Pacific, China's tactics to obtain technology have been aggressive and include forced technology transfer, intellectual property theft and access denial to Chinese markets.[129] Furthermore, China's technological prowess has been fueled by extraordinary economic growth.

While China's mercantilist economy has experienced significant growth since the reforms initiated by Deng Xiaoping, the recent pace of modernization and infrastructure

[126] Ibid., 50, 51.
[127] Ibid., 5.
[128] Robert D. Atkinson, "House Committee on Foreign Affairs, Subcommittee on Asia and the Pacific Hearing on China's Technological Rise." *Political Transcript Wire*, 2017.
[129] Ibid., 6

development has been remarkable. According to the World Bank, China's GDP growth rate has averaged nearly 10% annually and has brought more than 800 million people out of poverty since transitioning to a market-based economy in 1978.[130] Although their growth has slowed since 2011, China surpassed the U.S. as the world's largest economy (measured by purchasing power parity) in 2016 and is currently the world's largest exporter and trading nation.[131] Some forecasts estimate that China will fully overtake the U.S. economy within fifteen years. Part of Chinese President Xi JinPing's "Chinese Dream" of rejuvenation and returning China to global superpower status by 2049 is its One Belt One Road (OBOR) initiative, which includes a massive infrastructure plan across continental Asia. OBOR could potentially encompass 65 countries, 70% of the global population, and a Chinese investment of approximately $4 trillion.[132] While touted as an economic initiative, the plan also presents strategic and geo-political implications.

China's offensive capabilities continue to increase both in quantity and technological quality. The People's Liberation Army (PLA) is currently the world's largest active military at approximately 2.3 million, and is as large as 3.5 million if inclusive of paramilitary and reserve forces as of 2015.[133] The Army continues to invest in the mechanization of combat brigades and high mobility infantry brigades, while the Navy, currently the largest in Asia with a fleet of 300 surface ships, continues longer range modernization to expand its blue

---

[130] World Bank, accessed December 8, 2017, http://www.worldbank.org/en/country/china/overview.
[131] CIA World Factbook, accessed December 8, 2017, https://www.cia.gov/library/publications/the-world-factbook/geos/in.html.
[132] Jonathan Hillman, "OBOR on the Ground: Evaluating China's 'One Belt, One Road' Initiative at the Project Level," Prepared for the Naval War College Workshop on China's Silk Road Initiative, Honolulu, Hawaii, November 2016.
[133] Anthony H. Cordesman and Steven Colley, "Chinese Strategy and Military Modernization: A Comparative Analysis," *Center for Strategic and International Studies*, 2015.

water operations.[134] In addition to developing expeditionary amphibious assault capabilities, the PLA-N is also increasing its submarine fleet, which is estimated to reach 78 by 2020.[135] China's Air Force, the third largest in the world, has 2,100 combat aircraft; is the only country other than the U.S. to possess two concurrent stealth fighter programs; and continues to invest in UAV, Drone, and ISR program development.[136] According to the U.S. National Air and Space Intelligence Center, "China has the most active and diverse ballistic development program in the world" and continues to grow short range, middle range, and inter-continental ballistic missile arsenals.[137] China possesses between 55-65 nuclear ICBMs but maintains a no first use policy.[138]

While the Chinese government proclaims its "peaceful rise" agenda and continues making strides in the realm of economics and soft power, not all of its actions have been so peaceable. Nowhere is this more glaring than in the South China Sea. China's self-proclaimed nine-dash line and island reef construction in the Spratly Islands have significant implications on territorial waters, freedom of navigation, commercial shipping and international law.[139] China currently has eight outposts in the Spratleys and construction of infrastructure continues with the potential capacity to maintain three fighter regiments.[140] Additionally, their use of coast guard and maritime militia assets for low-intensity coercive

---

[134] United States, Department of Defense, "Military and Security Developments Involving the People's Republic of China: A Report to Congress Pursuant to the National Defense Authorization Act for Fiscal Year, 22, 24.
[135] Ibid., 24, 83.
[136] Anthony H. Cordesman, Steven Colley, "Chinese Strategy and Military Modernization in 2015: A Comparative Analysis," 278, 295, 297.
[137] Ibid., 308.
[138] Ibid., 340.
[139] Florian Dupuy and Pierre-Marie Dupuy, "A Legal Analysis of China's Historic Rights Claim in the South China Sea," *The American Journal of International Law* 107, No. 1 (2013): 124-141; Ben Dolven, Jennifer K. Elsea, Susan V. Lawrence, Ronald O'Rourke, and Ian E. Rinehart, "Chinese Land Reclamation in The South China Sea: Implications and Policy Options," *Current Politics and Economics of Northern and Western Asia* 24, No. 2 (2015): 319-351.
[140] United States, Department of Defense, "Military and Security Developments Involving the People's Republic of China: A Report to Congress Pursuant to the National Defense Authorization Act for Fiscal Year, 12.

actions in response to fishing and maritime territory disputes continues in the East and South China Seas, resulting in heightened tensions.[141] China's aggressive nature of "salami slicing" in the East and South China Seas calls into question their true intentions.

Conclusion

As the future of the maritime domain continues to grow in complexity and competition from near peer competitors such as China, it is crucial that concepts of underway replenishment adapt to ensure compatibility with both strategic guidance and contested operating environments. Existing technologies, such as undersea basing, autonomous and unmanned undersea vehicles, autonomous shipping, and additive manufacturing/three dimensional printing may offer the increased flexibility and agility needed for effective logistics sustainment. Additionally, threats persist to the U.S.'s ability to maintain a comparative military advantage over potential adversaries, including internal process challenges and a rising China in the Asia-Pacific region. In order to maintain superiority across all warfare domains, a reimagining of current processes and operations is paramount, especially at-sea replenishment and logistics concepts of operation.

[141] Ibid.

Bibliography

Atkinson, Robert D. "House Committee on Foreign Affairs, Subcommittee on Asia and the Pacific Hearing on China's Technological Rise." *Political Transcript Wire*. 2017.

Axe, David. *The US Navy Wants Undersea Gas Stations for Underwater Drones*. Motherboard. VICE. Accessed May 2, 2018. https://motherboard.vice.com/en_us/article/qvxmv3/the-us-navy-wants-undersea-gas-stations-for-underwater-drones.

Boeing Company. Echo Voyager Project XLUUV Brief. Boeing Proprietary. Releasable to U.S. Government Personnel Only-Business Sensitive. Presentation for Naval War College. Don Randall, September 26, 2017.

Boeing Company Echo Voyager Product Sheet. Accessed March 3, 2018. http://www.boeing.com/resources/boeingdotcom/defense/autonomous-systems/echo-voyager/echo_voyager_product_sheet.pdf.

CIA World Factbook. Accessed December 8, 2017. https://www.cia.gov/library/publications/the-world-factbook/geos/in.html.

Conde Nast Traveler. Accessed January 14, 2018. https://www.cntraveler.com/galleries/2016-07-09/11-coolest-underwater-hotels-in-the-world/3.

Cordesman, Anthony H. and Steven Colley. "Chinese Strategy and Military Modernization: A Comparative Analysis." *Center for Strategic and International Studies*. 2015.

Cousteau Organization. Conshelf I, II & III. Accessed March 1, 2018. https://www.cousteau.org/english/precontinent-i--ii-et-iii.php.

Defense Advanced Research Projects Agency. ACTUV "Sea Hunter" Prototype Transitions to Office of Naval Research for Further Development. Accessed May 10, 2018, https://www.darpa.mil/news-events/2018-01-30a.

Dolven, Ben, Jennifer K. Elsea, Susan V. Lawrence, Ronald O'Rourke, and Ian E. Rinehart. "Chinese Land Reclamation in The South China Sea: Implications and Policy Options." *Current Politics and Economics of Northern and Western Asia* 24, No. 2 (2015): 319-351.

Dupuy, Florian and Pierre-Marie Dupuy. "A Legal Analysis of China's Historic Rights Claim in the South China Sea." *The American Journal of International Law* 107, No. 1 (2013): 124-141.

Florida International University. Medina Aquarius Program. Accessed March 1 2018. https://aquarius.fiu.edu/.

Grady, John. U.S. Facing Looming Shortage of Merchant Mariners. *USNI News*. Accessed March 10, 2018. https://news.usni.org/2016/03/22/u-s-facing-looming-shortage-of-merchant-mariners.

Hart, John. Additive Manufacturing. MIT 2.008x, Lecture Slides. (November 2016). Accessed February 20, 2018. https://www.slideshare.net/AJohnHart/additive-manufacturing-2008x-lecture-slides.

Hellwarth, Ben. Sealab: America's Forgotten Quest to Live and Work on the Ocean Floor. 1st Simon & Schuster hardcover ed., New York: Simon & Schuster. 2012. 109.

Hillman, Jonathan. "OBOR on the Ground: Evaluating China's 'One Belt, One Road' Initiative at the Project Level." Prepared for the Naval War College Workshop on China's Silk Road Initiative. Honolulu, Hawaii. November 2016.

Johnson, Tim. "The US Merchant Marine Fleet Is Dying — And It May Hurt America's Ability To Wage War Abroad." McClatchy Washington Bureau, Task and Purpose. Accessed on May 15, 2018. https://taskandpurpose.com/us-mercant-marine-fleet-military/.

Keller, Jared. "The Navy can now 3D-print submarines on the fly for SEALs." Business Insider. Accessed on February 23, 2018. http://www.businessinsider.com/the-navy-can-now-3d-print-submarines-the-fly-seals-2017-7.

Louis, M.J., T. Seymour, and J. Joyce. "3D opportunity for the Department of Defense: Additive manufacturing fires up (A Deloitte series on additive manufacturing)." (2014). 1-28.

Murray, John. "Papa Topside, Captain George F. Bond, MC, USN." Faceplate, vol. 9, no. 1, (February 2005): 8-9.

Newman, Jeff. "Hitting Print: Navy On Board with Additive Manufacturing." Naval Aviation News. Accessed on February 23, 2018. http://navalaviationnews.navylive.dodlive.mil/2017/06/08/hitting-print-navy-on-board-with-additive-manufacturing/.

Office of the Director National Intelligence. "Global Trends 2030: Alternative Worlds." A publication of the National Intelligence Council. (2012). https://www.dni.gov/files/documents/GlobalTrends_2030.pdf.

Office of Naval Research. SEALAB Manned Undersea Habitat. Accessed on March 1, 2018, https://www.onr.navy.mil/en/About-ONR/History/tales-of-discovery/sealab.

Paschoa, Claudio. A Short History of Underwater Labs. Marine Technology News. (June 18, 2014). Accessed March 1, 2018. https://www.marinetechnologynews.com/blogs/short-history-of-underwater-labs-700486.

Prabhakar, Arati. "Breakthrough Technologies for National Security." *Defense Advanced Research Projects Agency (DARPA), Tech. Rep.* (2015). Accessed February 23, 2018, https://www.darpa.mil/attachments/DARPA2015.pdf.

Richardson, John M. "A Design for Maintaining Maritime Superiority." Naval War College Review 69, no. 2 (2016).

Richardson, John M. "The Future Navy." (May 2017). Accessed March 3, 2018, http://www.navy.mil/navydata/people/cno/Richardson/Resource/TheFutureNavy.pdf.

Rolls-Royce. Accessed March 5, 2018. https://www.rolls-royce.com/media/press-releases/yr-2017/12-09-2017-rr-reveals-plans-for-autonomous-naval-vessel.aspx.

Rolls-Royce. Info Sheet. Accessed March 5, 2018. http://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/customers/marine/ship-intel/rr-ship-intel-aawa-8pg.pdf.

Rolls-Royce. Ship Intelligence Marine. Autonomous Ships: The Next Step. Accessed March 3, 2018. http://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/customers/marine/ship-intel/rr-ship-intel-aawa-8pg.pdf.

Saarni, Jouni, Sini Nodberg-Davies, Hannu Makkonen. Rolls-Royce Ship Intelligence Marine. Advanced Autonomous Waterborne Applications Initiative (AAWA). *Remote and Autonomous Ships: The Next Steps,* 2016. pg: 83-85. http://www.rolls-royce.com/products-and-services/marine/ship-intelligence.aspx#section-overview1.

Saunders, Sarah. "US Navy and ORNL Team Up to Develop the Military's First 3D Printed Submarine Hull on the BAAM." 3DPrint.Com. Accessed on February 23, 2018. https://3dprint.com/181795/navy-ornl-3d-printed-sub-hull/.

Shea, Richard, Nicole Santos, and Robert Appleton. "Additive Manufacturing in the DoD." (2015): 1-31. http://www.iceaaonline.com/ready/wp-content/uploads/2016/06/BC05-paper-3D-Printing-DOD.pdf.

Strassler, Robert B. Thucydides. 1937, and Richard Crawley 1840-1893. The Landmark Thucydides: A Comprehensive Guide to the Peloponnesian War. Free Press trade pbk. ed. New York: Free Press, 2008.

Supply Advisory Team. Future Logistics Concepts Brief. 1-13.

Trauthwein, Greg. World's First Autonomous Shipping Company Formed. *Marine Link*. April 4, 2018. Accessed April 20, 2018. https://www.marinelink.com/news/autonomous-shipping435906.

United States. Department of Defense. National Defense Strategy Summary. Washington D.C.: Department of Defense, 2018.

United States. Department of Defense. Office of the Secretary of Defense and United States. Department of Defense. "Military and Security Developments Involving the People's Republic of China: A Report to Congress Pursuant to the National Defense Authorization Act for Fiscal Year." *Military and Security Developments Involving the People's Republic of China*, (May 15, 2017): 1-106.

United States. Government Accountability Office. Navy Readiness. Actions Needed to Maintain Viable Surge Sealift and Combat Logistics Fleets: Report to Congressional Committees. Washington, D.C.: United States Government Accountability Office. 2017, 11-16.

United States. Secretary of the Navy. Ray Mabus. Memorandum for Chief of Naval Operations. Additive Manufacturing/3-D Printing. September 3, 2015.

Walsh, Don. *One Little House Remains on the Bottom of the Sea*. Vol. 128, Annapolis: United States Naval Institute. 2002.

Walt, Stephen M. *The Origins of Alliances*. (Ithaca: Cornell University Press, 1987).

Weisgerber, Marcus. Accessed March 3, 2018. http://www.defenseone.com/business/2017/06/boeing-shipbuilder-team-build-giant-underwater-drones/138524/.

Wohlers, Terry. "Additive Manufacturing and Composites: An Update." Composites World 3, no. 6 (06, 2017): 6.

World Bank. Accessed December 8, 2017. http://www.worldbank.org/en/country/china/overview.

Yi, Wen. “The Making of an Economic Superpower —Unlocking China’s Secret of Rapid Industrialization.” Research Division Federal Reserve Bank of St. Louis Working Paper Series. Working Paper 2015-006B (June 2015): 1-180.