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Benchmarking Naval Shipbuilding with 3D Laser Scanning, Additive Manufacturing, and Collaborative Product Lifecycle Management

20 September 2015

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Abstract

The U.S. Navy estimates that it will cost \$16.7 billion per year for new-ship construction to become a fleet of 306 battle force ships over the next 30 years. It is critical that the Navy capture the full benefits of new technologies such as three-dimensional scanning (3DLS), product lifecycle management (PLM), and additive manufacturing (AM) to reduce costs while still meeting mission needs. This project examines the use of 3DLS, PLM, and AM by non-shipbuilding industries as a basis for estimating potential naval shipbuilding savings. The research was conducted in two phases. In the first phase, secondary research was conducted on the three technologies used by various industries, while in the second phase, a model on the potential cost and efficiency savings that could be derived from the use of those technologies was developed. The ultimate goal is to develop insight into the amount and timing of technology costs and potential savings from use of the technologies in shipbuilding. Also, in phase two, recommendations are provided to Navy planners concerning the most effective and efficient strategy for exploiting these technologies. This preliminary report discusses some of the findings during phase one. It provides an overview of the Navy's shipbuilding plans, and a framework for understanding of 3DLS, AM, and CPLM technologies, as well as potential applications to commercial shipbuilding.

Keywords: shipbuilding, cost savings, technology, implementation strategy



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Disclaimer: The views represented in this report are those of the author and do not reflect the official policy position of the Navy, the Department of Defense, or the federal government.



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I. Introduction

The U.S. Navy estimates that it will cost \$16.7 billion per year for new-ship construction to become a fleet of 306 battle force ships over the next 30 years. It is critical that the Navy capture the full benefits of new technologies such as three-dimensional scanning (3DLS), product lifecycle management (PLM), and additive manufacturing (AM) to reduce costs while still meeting mission needs. Research supports the adoption and use of these commercially available technologies yet does not address their use in naval shipbuilding. Cost savings estimates and strategies for technology adoption and use are important for capturing the full benefits of these technologies.

Our research project examines the use of 3DLS, PLM, and AM by non-shipbuilding industries as a basis for estimating potential naval shipbuilding savings. The research was conducted in two phases. In the first phase, secondary research was conducted on the three technologies used by various industries, while in the second phase, a model on the potential cost and efficiency savings that could be derived from the use of those technologies was developed. The ultimate goal is to develop insight into the amount and timing of technology costs and potential savings from use of the technologies in shipbuilding. Also, in phase two, recommendations are provided to Navy planners concerning the most effective and efficient strategy for exploiting these technologies.

This preliminary report discusses some of the findings during phase one. It provides an overview of the Navy's shipbuilding plans, and a framework for understanding of 3DLS, AM, and CPLM technologies, as well as potential applications to commercial shipbuilding.



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II. Naval Shipbuilding

The U.S. Navy will become a fleet of 306 battle force ships over the next 30 years, up from today's battle force of 289. In a report submitted to Congress in July 2014, implementing the Navy's 2015 shipbuilding plan covering fiscal years 2015 to 2044 will cost the Navy an estimated \$16.7 billion per year in constant FY2014 dollars (Office of Naval Operations, 2014).

The proposed battle force of 306 achieves the following:

1. aligns global presence requirements with national priorities;
2. increases forward basing/stationing of ships and systems;
3. improves payload capacity for SSNs replacing SSGNs; and
4. increases use of rotational civilian and military crews, providing more forward presence per ship (Office of Naval Operations, 2014)

The objective for 306 ships includes the following:

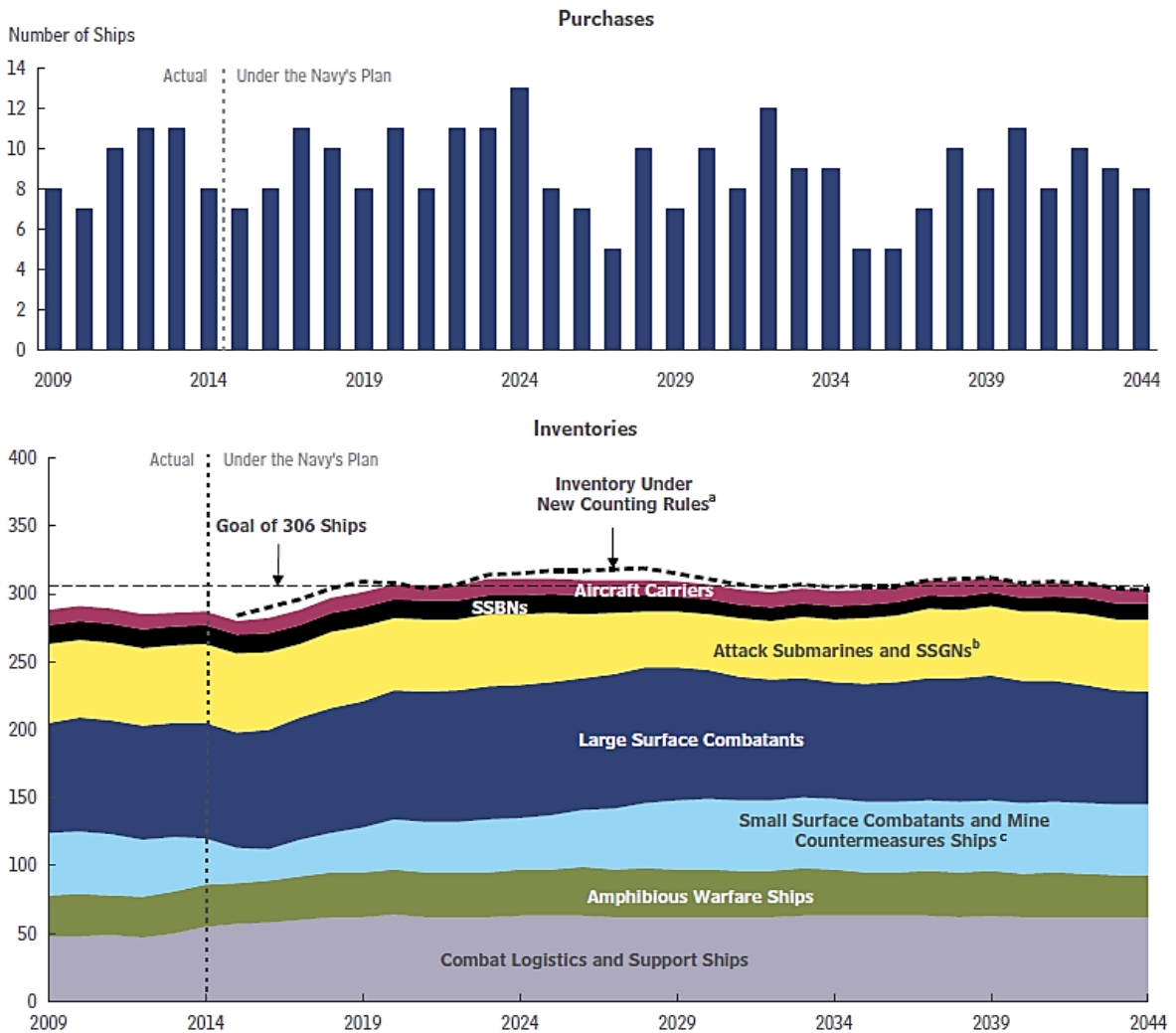
- 12 fleet ballistic missile submarines;
- 11 nuclear-powered aircraft carriers;
- 48 nuclear-powered attack submarines;
- 0–4 nuclear-powered cruise missile submarines;
- 88 large, multi-mission, surface combatants;
- 52 small, multi-role, surface combatants;
- 33 amphibious landing ships;
- 29 combat logistics force ships; and
- 33 support vessels.

The Navy plans to buy a total of 264 ships over the 2015–2044 period under the 2015 plan: 218 combat ships and 46 combat logistics and support ships. According to the Congressional Budget Office (CBO, 2014), given the rate at which the Navy plans to retire ships from the fleet, that construction plan would not achieve a fleet equal to the inventory goal of 306 ships until 2019 under new rules for counting ships that the Navy implemented this year (2015), or until 2022 under the old counting rules. Figure 1 shows the Navy's 2015 shipbuilding plans.



Figure 1: Navy Shipbuilding Plans (CBO, 2014)

Annual Ship Purchases and Inventories Under the Navy's 2015 Plan



Source: Congressional Budget Office (2014) based on data from the Department of the Navy.

Notes: The colored parts of the chart reflect the Navy's old counting rules.

SSBNs = ballistic missile submarines; SSGNs = guided missile submarines.

- a. Effective with the 2015 President's budget and shipbuilding plan, the Navy is modifying its method for counting battle force ships. The changes affect a small number of ship classes designated as (very) small combatants or logistics and support ships. Specifically, the Navy will now count Cyclone class patrol combatants that are based overseas (in the theater of operations) but not those that are based in the United States. It will treat Avenger class mine countermeasures ships the same way. The Navy will now also include the two hospital ships operated by the Military Sealift Command in the battle force. Patrol combatants and hospital ships did not count under the old rules, whereas all mine countermeasures ships did count, not just those in-theater.
- b. Although the Navy does not plan to build more SSGNs, four will be in service through the mid-2020s.
- c. Small surface combatants and mine countermeasures ships include littoral combat ships, Oliver Hazard Perry FFG-7 frigates, and Avenger class mine countermeasures ships.



The Navy estimates that over the entire 30-year shipbuilding plan, buying new ships specified in the 2015 plan would cost \$500 billion, and the estimated average budget for new ship construction (SCN) is \$16.7 billion per year. In the near-term planning years of FY2015–FY2024, the annual budget for new ship construction will be \$15.7 billion per year using FY2014 constant dollars and based on the cost of ships today (using current industrial base capacity and pricing). During the mid-term planning period (FY2025–FY2034), the average budget will be \$19.7 billion per year. In the far-term planning period, the average budget will be \$14.6 billion per year.

However, CBO estimates for new SCN in the Navy’s 2015 plan would actually total \$566 billion over 30 years, or an average of \$18.9 billion per year. Furthermore, additional costs of refueling aircraft carriers and other items (i.e., outfitting new ships) raises the overall average cost of the Navy’s plan to \$20.7 billion per year. In its estimate of new SCN costs for the 2015 shipbuilding plan, the CBO estimates costs 13% higher than the Navy’s over the next 30 years. The costs differences can be seen in Table 1. In the past, differences in cost estimates between the CBO and the Navy’s shipbuilding plans have been due to differences in how the CBO and the Navy treat inflation in Navy shipbuilding. Table 1 is a comparison of average annual costs estimated by the CBO and Navy, while Figure 2 shows the Navy’s estimates for annual funding for its long-range shipbuilding plan. Figure 3 shows the annual funding required for FY2015–FY2044.



Table 1. Comparison of Average Annual Costs Estimated by the Navy and the Congressional Budget Office (CBO, 2014)

Average Annual Shipbuilding Costs Under the Navy's 2015 Plan, by Decade				
	Near Term (2015–2024)	Midterm (2025–2034)	Far Term (2035–2044)	Total (2015–2044)
Navy's Estimates (Billions of 2014 dollars)				
New-Ship Construction	15.7	19.7	14.6	16.7
New-Ship Construction and Refueling of Nuclear-Powered Aircraft Carriers ^a	17.1	20.7	15.2	17.7
New-Ship Construction, Refueling of Nuclear-Powered Aircraft Carriers, and Other Items ^b	18.4	21.4	15.8	18.6
CBO's Estimates (Billions of 2014 dollars)				
New-Ship Construction	16.7	22.5	17.5	18.9
New-Ship Construction and Refueling of Nuclear-Powered Aircraft Carriers	18.0	23.5	18.1	19.9
New-Ship Construction, Refueling of Nuclear-Powered Aircraft Carriers, and Other Items	19.2	24.2	18.7	20.7
Percentage Difference Between the Navy's and CBO's Estimates				
New-Ship Construction	6	14	20	13
New-Ship Construction and Refueling of Nuclear-Powered Aircraft Carriers	6	13	19	12
New-Ship Construction, Refueling of Nuclear-Powered Aircraft Carriers, and Other Items	4	13	18	11
Memorandum (Billions of 2014 dollars):				
CBO's Estimate of the Costs of New-Ship Construction Needed to Meet Nearly All All Inventory Goals in Each Year	19.0	22.6	17.6	19.7
Costs of Mission Packages for Littoral Combat Ships	0.4	0.1	0.3	0.3

Source: Congressional Budget Office based on data from the Department of the Navy.

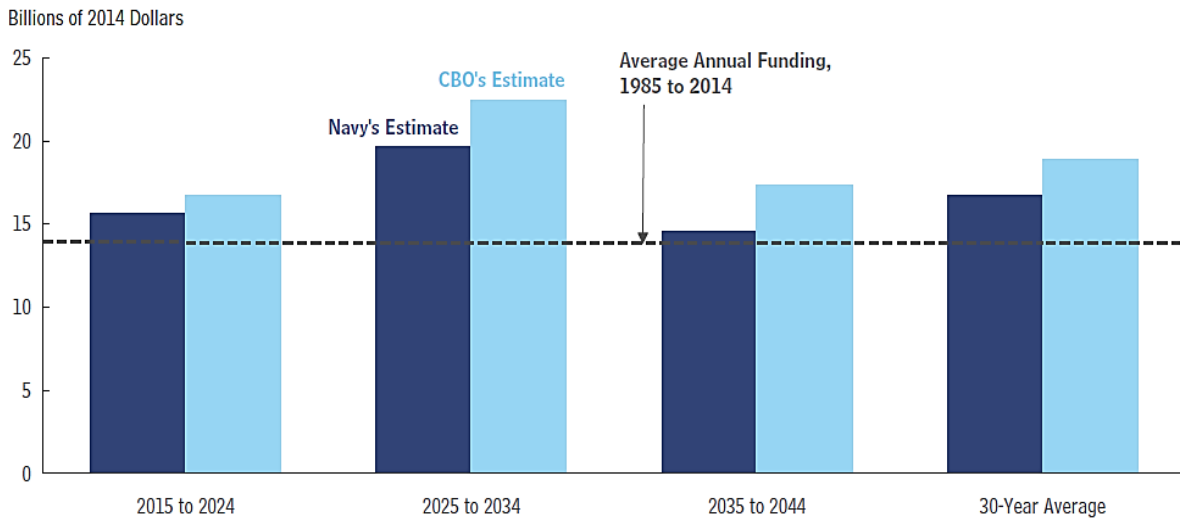
Note: Other items include ship conversions, construction of ships that are not part of the Navy's battle force (oceanographic survey ships, for instance), training ships, outfitting and postdelivery costs (which include the purchase of many smaller tools and pieces of equipment needed to operate a ship but not necessarily provided by the manufacturing shipyard as part of ship construction), and smaller items. Actual costs for the Navy's shipbuilding accounts over the past 30 years averaged about \$16 billion per year for all items.

- a. These numbers represent the Navy's estimate for new-ship construction and CBO's estimate for the refueling of nuclear-powered aircraft carriers.
- b. These numbers represent the Navy's estimates for both new-ship construction and cost-to-complete funding for ships purchased in prior years, and CBO's estimates for the refueling of nuclear-powered aircraft carriers and other items.



Figure 2. Navy Shipbuilding Estimates (CBO, 2014)

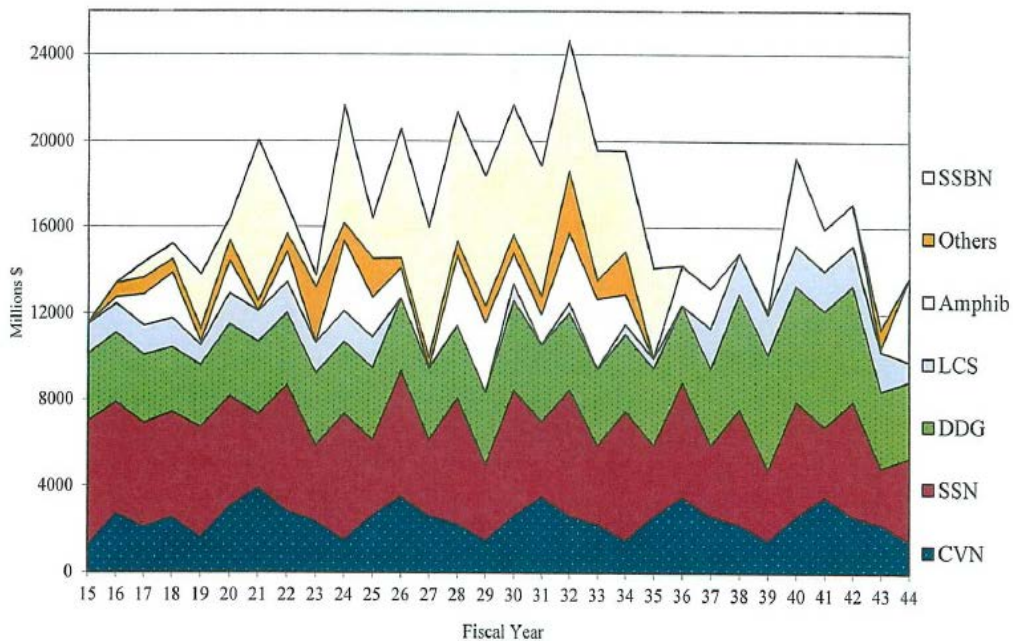
Average Annual Costs of New-Ship Construction Under the Navy's 2015 Plan



Source: Congressional Budget Office based on data from the Department of the Navy.

Note: Costs of new-ship construction exclude funds for some activities that are typically funded in the Navy's shipbuilding accounts, such as refueling of nuclear-powered aircraft carriers, ship conversions, construction of ships that are not part of the Navy's battle force (oceanographic survey ships, for instance), training ships, outfitting and post-delivery (which include the purchase of many smaller tools and pieces of equipment that are needed to operate a ship but are not necessarily provided by the manufacturing shipyard as part of ship construction), and smaller items. Costs for the mission packages for littoral combat ships, which are not funded in the Navy's shipbuilding accounts, also are not included.

Figure 3. Annual Funding Required for Navy Long-Range Shipbuilding Plan (FY2015–FY2044) (Office Naval Operations, 2014)



For FY2015, the Navy’s proposed budget requests funding for the procurement of seven new battle force ships that include two Virginia-class attack submarines, two DDG-51 class Aegis destroyers, and three Littoral Combat Ships (LCSs). The Navy’s proposed FY2015–FY2019 five-year shipbuilding plan includes a total of 44 ships, as seen in Table 2. An additional 220 ships would be purchased through 2044, for a total of 264 ships over 30 years (averaging about nine ships per year).

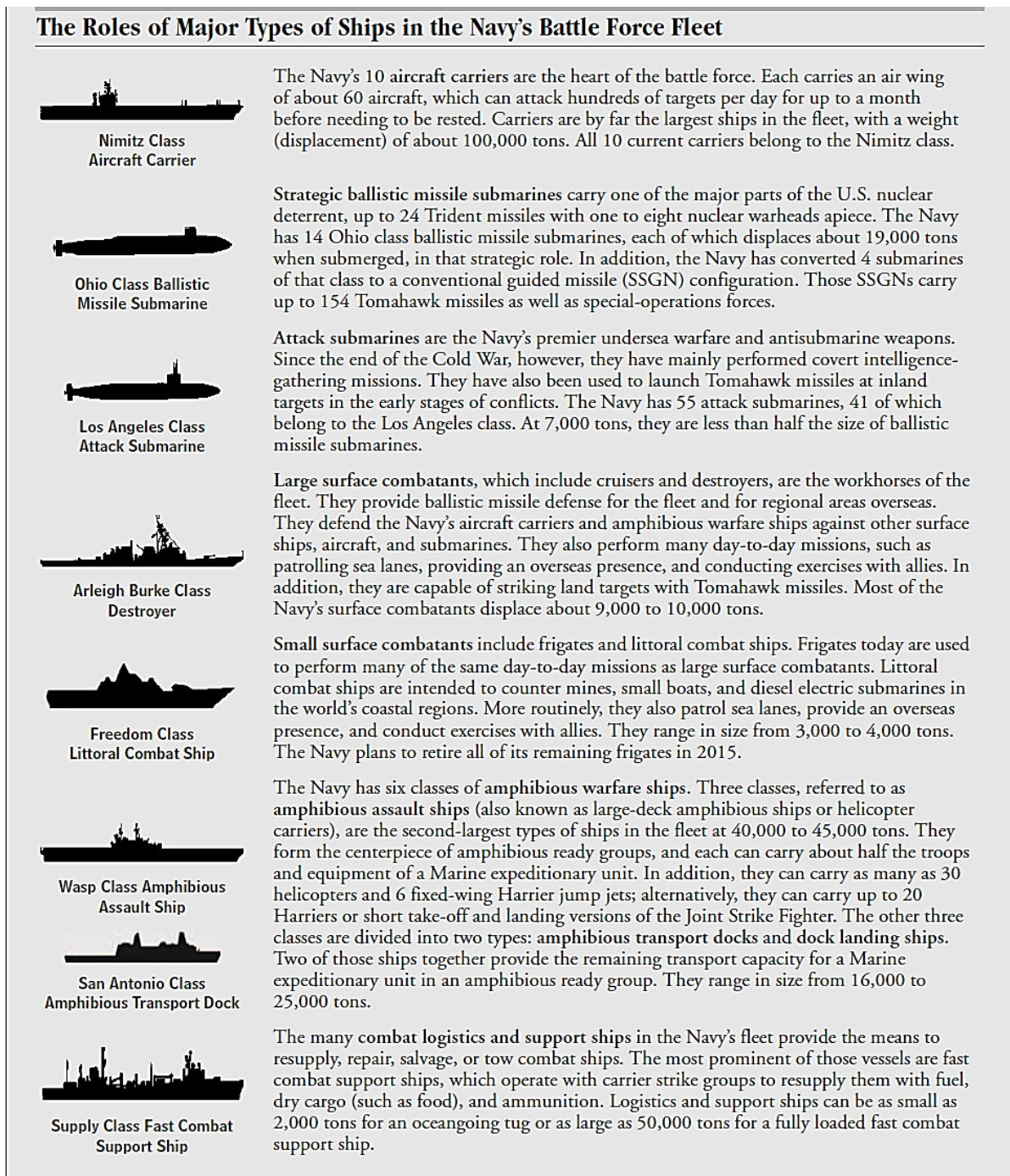
**Table 2. Navy FY2014 Five-Year (FY2015–FY2019) Shipbuilding Plan
(Office of Naval Operations, 2014)
Battle Force Ships**

Ship type	FY15	FY16	FY17	FY18	FY19	Total
Ford (CVN-78) class aircraft carrier				1		1
Virginia (SSN-774) class attack submarine	2	2	2	2	2	10
Arleigh Burke (DDG-51) class destroyer	2	2	2	2	2	10
Littoral Combat Ship (LCS)	3	3	3	3	2	14
LHA(R) amphibious assault ship			1			1
Fleet tug (TATF)			2	1	1	4
Mobile Landing Platform (MLP)/Afloat Forward Staging Base (AFSB)			1			1
TAO(X) oiler		1		1	1	3
TOTAL	7	8	11	10	8	44

Figure 4 identifies the major types of ships in the Navy’s force fleet.



**Figure 4. The Major Types of Ships in the Navy's Force Fleet
(CBO, 2014)**



Source: Congressional Budget Office.

Note: Ship silhouettes are not to scale.



The Navy's 2015 shipbuilding plan states that the service's overall inventory goal is 306 battle force ships, as shown in Table 3. Table 4 shows the annual projected force levels resulting from FY2015 30-Year (FY2015–FY2044). It should be noted that the Navy's shipbuilding plan falls short of meeting the service's inventory goals for some types of ships in some years.

Table 3. Navy FY2015 30-Year (FY2015–FY2044) Shipbuilding Plan (CRS 2014)

FY	CVN	LSC	SSC	SSN	SSBN	AWS	CLF	Supt	Total
15		2	3	2					7
16		2	3	2			1		8
17		2	3	2		1		3	11
18	1	2	3	2			1	1	10
19		2	2	2			1	1	8
20		2	3	2		1	1	2	11
21		2	3	1	1		1		8
22		2	3	2		1	1	2	11
23	1	2	3	1			1	3	11
24		2	3	2	1	2	1	2	13
25		2	3	1			1	1	8
26		2		2	1	1	1		7
27		2		1	1		1		5
28	1	2		2	1	2	1	1	10
29		2		1	1	1	1	1	7
30		2	1	2	1	1	1	2	10
31		2		1	1	1	1	2	8
32		2	1	2	1	2	1	3	12
33	1	2		1	1	1	1	2	9
34		2	1	2	1	1		2	9
35		2	1	1	1				5
36		2		2		1			5
37		2	4	1					7
38	1	3	4	2					10
39		3	4	1					8
40		3	4	2		2			11
41		3	4	1					8
42		3	4	2		1			10
43	1	2	4	1			1		9
44		2	2	2		2			8

Source: FY2015 30-year (FY2015-FY2044) shipbuilding plan.



Table 4. Projected Force Levels Resulting from FY2015 30-Year (FY2015–FY2044) Shipbuilding Plan (CRS, 2014)

	CVN	LSC	SSC	SSN	SSGN	SSBN	AWS	CLF	Supt	Total
306 ship plan	11	88	52	48	0	12	33	29	33	306
FY15	10	85	19/26	54	4	14	30	29	29/32	274/284
FY16	11	88	23/30	53	4	14	31	29	27/30	280/290
FY17	11	90	27/34	50	4	14	32	29	29/32	286/296
FY18	11	91	31/38	52	4	14	33	29	29/32	295/304
FY19	11	93	35/40	51	4	14	33	29	31/34	301/309
FY20	11	95	36/37	49	4	14	33	29	33/36	304/308
FY21	11	96	36/33	49	4	14	33	29	32/35	304
FY22	11	97	38/36	48	4	14	33	29	32/35	306/307
FY23	12	98	39	49	4	14	33	29	33/36	311/314
FY24	12	98	41/40	48	4	14	34	29	33/36	313/315
FY25	11	98	43	47	4	14	34	29	34/37	314/317
FY26	11	97	46	45	2	14	36	29	34/37	314/317
FY27	11	99	49	44	1	13	35	29	34/37	315/318
FY28	11	100	52	41	0	13	36	29	34/37	316/319
FY29	11	98	52	41	0	12	35	29	34/37	312/315
FY30	11	95	52	41	0	11	35	29	34/37	308/311
FY31	11	91	52	43	0	11	34	29	34/36	305/307
FY32	11	89	52	43	0	10	34	29	35/37	303/305
FY33	11	88	52	45	0	10	35	29	35/37	305/307
FY34	11	86	52	46	0	10	34	29	35/37	303/305
FY35	11	87	52	48	0	10	32	29	35/37	304/306
FY36	11	88	52	49	0	10	32	29	35	306
FY37	11	90	52	51	0	10	33	29	34	310
FY38	11	91	52	50	0	10	33	29	35	311
FY39	11	92	52	51	0	10	33	29	34	312
FY40	10	90	52	51	0	10	32	29	34	308
FY41	10	89	52	51	0	11	33	29	34	309
FY42	10	87	52	52	0	12	32	29	34	308
FY43	10	84	52	52	0	12	31	29	34	304
FY44	10	83	52	52	0	12	31	29	34	303

Source: FY2015 30-year (FY2015-FY2044) shipbuilding plan.

Note: Figures for support ships include five JHSVs transferred from the Army to the Navy and operated by the Navy primarily for the performance of Army missions.

Key: FY = Fiscal Year; CVN = aircraft carriers; LSC = surface combatants (i.e., cruisers and destroyers); SSC = small surface combatants (i.e., frigates, Littoral Combat Ships [LCSs], and mine warfare ships); SSN = attack submarines; SSGN = cruise missile submarines; SSBN = ballistic missile submarines; AWS = amphibious warfare ships; CLF = combat logistics force (i.e., resupply) ships; Supt = support ships.

Note: Where two figures are shown, the first is the figure using existing rules for counting battle force ships, and the second is the figure using the Navy's proposed modified rules for counting battle force ships.



Two large corporations dominate Navy shipbuilding: General Dynamics (GD) and Huntington Ingalls Industries (HII). These two corporations have six shipyards. Another two shipyards shown in Table 5, Austal USA and the Fincantieri Marine Group, build the LCSs, yielding a total of eight shipyards that build the majority of the Navy's fleet.

Table 5. Major Private Shipyards (Shipbuilders Council of America [SCA], 2014)

MAJOR U.S. PRIVATE SHIPYARDS		
	Shipyards	Recent Products
General Dynamics	Bath Iron Works	DDG-51 class, DDG 1000 class
	Electric Boat	<i>Virginia</i> class SSN
	NASSCO	RO-RO Strategic Sealift Ships, TAKE, Auxiliary Ships, MLP
Huntington Ingalls Industries	Newport News Shipbuilding	<i>Ford</i> class CVN, <i>Virginia</i> class SSN
	Ingalls/Avondale	LPD 17 class, DDG 51 class, LHA 6 class
Austal	Austal USA	Littoral Combat Ship, JHSV
Fincantieri Marine Group	Marinette Marine Corporation	Littoral Combat Ship

Funding for new ship construction is from the Shipbuilding and Conversion, Navy (SCN) appropriation. SCN funds are used to construct new ships and convert existing ships, including service-life extensions, and nuclear refueling and complex overhauls (RCOH). It is a multi-year appropriation that normally remains available for obligation for five fiscal years or the obligation work limiting date (OWLD) of the ship under construction. For the past seven years, the SCN represented an average 33% of the Navy's and 12% of the Defense Department's overall procurement budget, and has averaged seven combatants per year (SCA, 2014).



III. Product Lifecycle Management

Product Lifecycle Management (PLM) is defined as an

“integrated, information-driven approach comprised of people, processes/practices, and technology, to all aspects of a product's life, from its design through manufacture, deployment and maintenance—culminating in the product's removal from service and final disposal. By trading product information for wasted time, energy, and material across the entire organization and into the supply chain, PLM drives the next generation of lean thinking.” (Greaves, 2006, p. 1)

According to the website glossary for CIMdata,

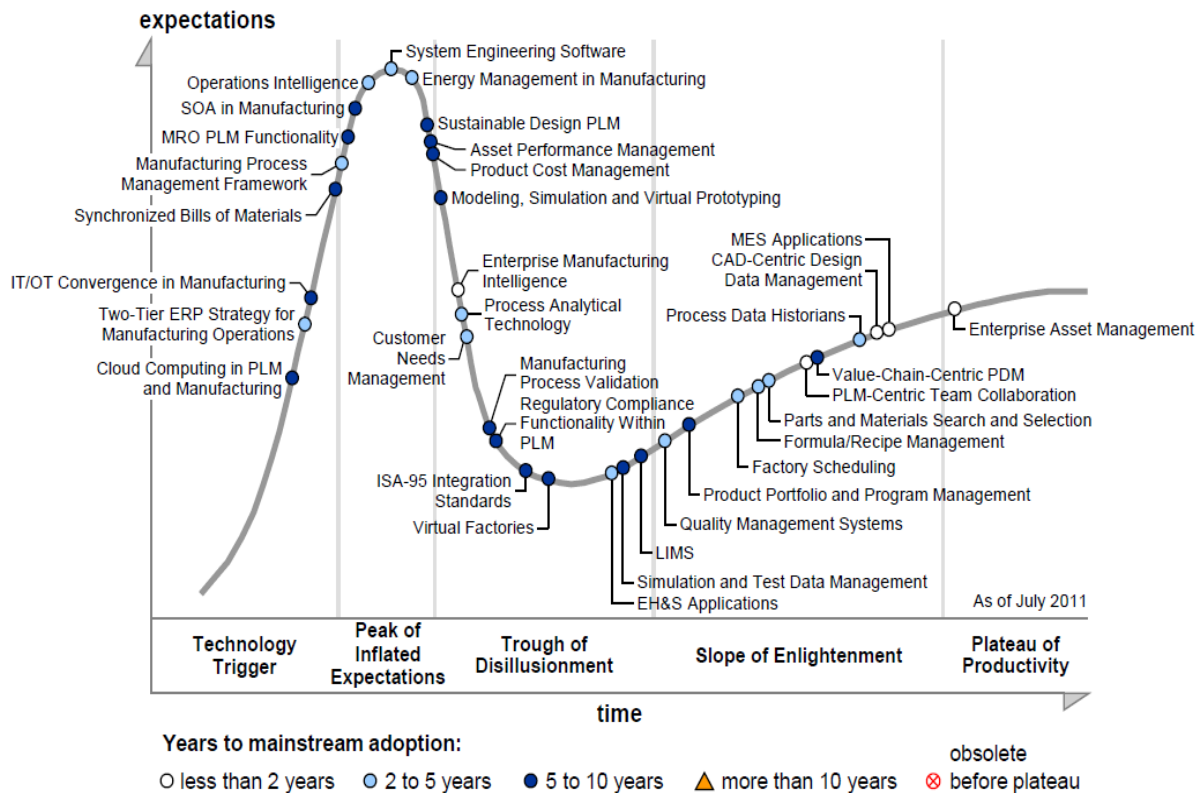
“PLM a strategic business approach that applies a consistent set of business solutions in support of the collaborative creation, management, dissemination, and use of product definition information across the extended enterprise, and spanning from product concept to end of life – integrating people, processes, business systems, and information. PLM forms the product information backbone for a company and its extended enterprise.”

The Gartner Group (2014) defines “PLM is a discipline for guiding products and product portfolios from ideas through retirement to create the most value for businesses, their partners, and their customers.” Although definitions differ, there is agreement that PLM is a systematic approach to managing the series of changes from its design and development to its ultimate retirement or disposal.

PLM has been used by the automotive, aerospace, and other industries that build very large, very complex products and systems. It was designed to provide stakeholders with current views of every product throughout its lifecycle and to facilitate decision-making and corrective actions if necessary. In the Gartner Group's (2014) PLM Hype Cycle seen in Figure 5, PLM is in various stages of development.



Figure 5. Hype Cycle for Manufacturing Product Life Cycle Management, 2011 (Halpern, 2012)



Gartner Group (2014) defines five key phases of a technology's lifecycle:

- **Technology Trigger.** A new technology triggers excitement for the technology. There are early proof-of-concept stories and media interest; however, there are no usable products and un-confirmed commercial viability at this phase.
- **Peak of Inflated Expectations.** There are several early successes, in conjunction with several failures. Although some companies adopt the technology early, many do not.
- **Trough of Disillusionment.** Interest lessens as implementations fail to deliver. An industry shakeout occurs.
- **Slope of Enlightenment.** The technology's benefits becoming more understood, so second- and third-generation products emerge.
- **Plateau of Productivity.** Mainstream adoption of the technology.



PLM is a maturing market, as evidenced by Gartner Group’s (2014) survey of 62 companies from six industries. As seen in Table 6, companies in the automotive industry are the biggest spenders on PLM software—spending an average of \$7.2 million per deployment—followed by the machinery industry.

Table 6. Estimated Spending on Product Lifecycle Management Software per Deployment (\$ Millions) (Halpern, 2012)

Industry	50% of Deployments Spent at Least	Minimum Spending Reported
Consumer Goods	\$2.4 million	\$300,000
Machinery	\$2.7 million	\$500,000
Automotive	\$7.2 million	\$1 million
High Tech	\$3.2 million	\$100,000
Aero & Defense	\$2.3 million	\$300,000
Others	\$2.7 million	\$200,000

Product Lifecycle Management In Shipbuilding

PLM can be used in shipbuilding to build and maintain the next generation of ships. It spans the entire shipbuilding enterprise and lifecycle to enable shipbuilders to integrate organizational knowledge, automate processes throughout the product lifecycle and improve efficiency, accuracy, and execution to reduce time to delivery. PLM can

- Provide shipbuilders and suppliers with access to relevant data.
- Achieve greater performance and lower ownership cost, and offer higher fleet availability and reliability, and achieve greater quality and compliance with the latest marine safety and regulatory requirements.
- Make ships easier to build and repair, lowering construction, service, and total ownership costs.
- Link shipbuilders with suppliers in the production schedule and all with design aspects.



A wide range of industries using PLM are finding that 3DLS is a critical tool in closing the gap between physical objects in the real world and in the digital design world. The aerospace, automotive, consumer products, manufacturing, and heavy industries all have benefited from faster time to market, improved quality, and reduced warehousing costs with 3D scanning. The next section looks into 3D laser scanning technology in further detail.



IV. 3D Laser Scanning

This section begins with a discussion of 3DLS and industries that use the technology. Two research projects funded by the National Shipbuilding Research Program (NSRP) in 2005 and 2006 are summarized with project findings, and the Navy's use of 3DLS is discussed.

3DLS technology has been used to achieve significant cost savings, optimize maintenance schedules, increase quality, improve safety, and reduce re-work. Commercial applications range from maritime and space applications to manufacturing and production. According to industry analysts, the industry's growth is fueled by the growing recognition that 3D aids in the design, fabrication, construction, operations, and maintenance processes. Benefits of 3DLS can be applied to shipbuilding.

Laser scanners use infrared laser technology to produce exceedingly detailed three-dimensional images of complex environments and geometries in only a few minutes. Millions of discrete measurements can be captured in every scan using 3DLS technology. The resulting images, called *point clouds*, are millions of 3D measurement points. A complete project may contain hundreds of millions or even billions of points, recreating the complex spatial relationships of the 3D environment.

The density of the points collected is controlled by the rotation speed of the scanner. The slower the scanner turns, the denser the pattern of points collected, while the faster the scanner turns, the less dense the resulting point cloud. 3D scanners can now be used to get complete or partial 3D measurements of any physical object without any contact with the physical object being captured. Figure 6 shows how a 3D model is made from a real object.

Figure 6. Real and 3D Model Comparison (Creaform, 2015)



Often used by offshore oil and gas companies to construct and repair oil rigs, 3DLS is very effective at documenting oil platforms and refineries to assist in engineering, maintenance, and planning processes. The aerospace and automotive industries have used 3DLS for retrofitting floors and measuring parts for accurate fit. Other industries using the technology include

- **Law Enforcement.** Used in crime scene documentation, forensics, and accident reconstruction.
- **Architectural and Civil Engineering.** Used to capture as-built documentation of existing buildings and structures, such as bridges; provides architects and contractors with exact dimensions. Building information models (BIMs) can be developed to retrofit projects.
- **Asset and Facility Management/Documentation.** With 3D documentation of complex factory and plant installations, users are provided with very precise 3D computer-aided design (CAD) data for use in facility management, maintenance, and asset documentation.
- **Surveying.** Used to complement or replace traditional tools, such as total stations, to fully capture manmade or natural objects for volume calculations, as-built surveys, and topographic surveys (FARO, 2014).

Applications of 3DLS in PLM include manufacturing, servicing, design, and concept areas, as shown in Figure 7.



Figure 7. Potential Applications of 3D Scanning in PLM (Creaform, 2015)



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V. Ship Check Data Capture Projects 2005 and 2006

Recognizing the potential of new technologies on the ship check process on the U.S. shipping industry, the NSRP funded two Ship Check Data Capture projects in 2005 and 2006. Objectives of both Ship Check Data Capture projects were to

1. develop a process that captures the as-built measurement data in digital/electronic format during a ship check;
2. process the as-built measurement data into 3D CAD models using available commercial-off-the-shelf (COTS) modeling technologies (software and hardware); and
3. provide a building block process for the anticipated development of the capabilities to generate 3D CAD models of the as-built space envelope from the geometric measurement data captured during the ship check.

Ship Check Data Capture 2005

Laser scanning, close-range photogrammetry, and other technologies capturing as-built ship conditions in digital format to create 3D electronic models were evaluated. The project's goals were to determine potential technology synergies producing cost-effective solutions, and to prototype a ship check data capture process that could be used by the U.S. shipbuilding industry. It was also anticipated that archived digital data would provide a cost-effective solution to the lifecycle cost management of ships.

Specific benefits from the software and hardware tested include

- creation of as-built 3D models and validation of as-built models to design models;
- reduction of costly design changes, improved design capability;
- reduced construction rework;
- accurate factory-fabricate in lieu of field-fabricate;
- reduced ship check costs: fewer days, fewer personnel;
- elimination of return visits to the ship for missed measurements; and
- measurements that are difficult or unsafe for human reach (NSRP 2005).

Initial results were so encouraging from this project that a nine-month follow-on project was awarded by the NSRP in 2006.



Ship Check Data Capture Follow-On 2006 Project

The NSRP's FY2006 follow-on ship check project evaluated the ship check process developed in the FY2005 project further and refined the ship check process for the U.S. shipbuilding and repair industry using available COTS technology. In this follow-up project, the team conducted a ship check onboard a surface ship at Bender Shipbuilding & Repair Company and conducted work onboard SSGN 729 to validate the data accuracy/repeatability of the SSGN 729 ship check data collected from the FY2005 project.

Performance improvement metrics were developed and tracked to compare the as-is practice with anticipated project results, as shown in Table 7. This project reported the cost/time savings metrics associated with post-processing the ship check data into 3D CAD models compared to create CAD models using the traditional ship check method with tape measures (see Table 8).

Table 7. Project Performance Improvement Measurements (NSRP, 2007)

Metric	"As-Is" Baseline	Project Goal	Tracking & Reporting Plan
<i>Time and cost to collect measurements onboard a ship and create 3D CAD models from this information.</i>	<i>Time and cost to create 3D CAD models using traditional ship check methods. This involves creating 2D sketches; taking measurements with tape measures, plumb bobs, etc.; recording measurements on the sketches; and creating 3D CAD models from this information.</i>	<i>Using new data capture and data processing methods to create 3D CAD models, reduce time by 35% and cost by 30% compared to "as-is" baseline methods.</i>	<i>Estimate time and cost associated with the use of traditional ship check methods and compare those to time and cost associated with the new data capture and data processing methods. Report the findings on time/cost savings at the end of the project.</i>

Table 8 shows the estimated cost savings of 37% and time savings of 39% realized for ship check data capture/post processing with the available COTS laser scanning technology hardware and software tools results when compared to traditional ship checks using tape measures. The estimated cost savings is 7% above the project goal of 30%, and the estimated time savings is 4% above the project goal of 35%. Further cost savings can be achieved by using laser scanning technology for ship checks from cost avoidance and minimized rework.



Table 8. Cost/Time Savings (Traditional vs. Laser Scanning) (NSRP, 2007)

	Traditional Ship Check/Creating As-built 3D CAD Model				Ship Check with Laser Scanning/Post Processing of As-built 3D CAD Model					
	(Estimate)				(Actual)					
	Total Labor Hours	Labor Cost	Expense Cost	Total Cost	Total Labor Hours	Labor Cost	Expense Cost	Total Cost	Total Cost Savings	Total Time Savings (Hours)
Total Number of Design Personnel	3				2					
Post processing		40	\$2,000	\$2,000		24	\$1,200	\$1,200	\$800	12
Number of hours for ship check	10	30	\$1,500	\$1,500	8	16	\$800	\$800	\$700	14
Travel time	16	48	\$2,400	\$2,400	16	32	\$1,600	\$1,600	\$800	16
Total expense days	3				3					
Estimated Travel Expense:										
Airfare \$400			\$1,200	\$2,427			\$800	\$1,648	\$779	
Lodging \$125			\$750				\$500			
Car Rental \$45			\$90				\$90			
Per Diem \$43			\$387				\$258			
Total Cost/Time		118	\$5,900	\$8,327		72	\$3,600	\$5,248	\$3,079	46

Ship Check Project Results - Cost/Time Savings Metrics

Realized Cost Savings = Total cost savings/Total cost for traditional methods
 = \$3,079/\$8,327 = 37%

Realized Time Savings = Total time savings/Total labor hours for traditional methods
 = 46/118 = 39%



Figure 8 shows the ship check process and equipment used in these two projects, while Figure 9 shows the process flow.

Figure 8. Ship Check Process with Laser Scanners and Uses of Ship Check Data (NSRP, 2007)

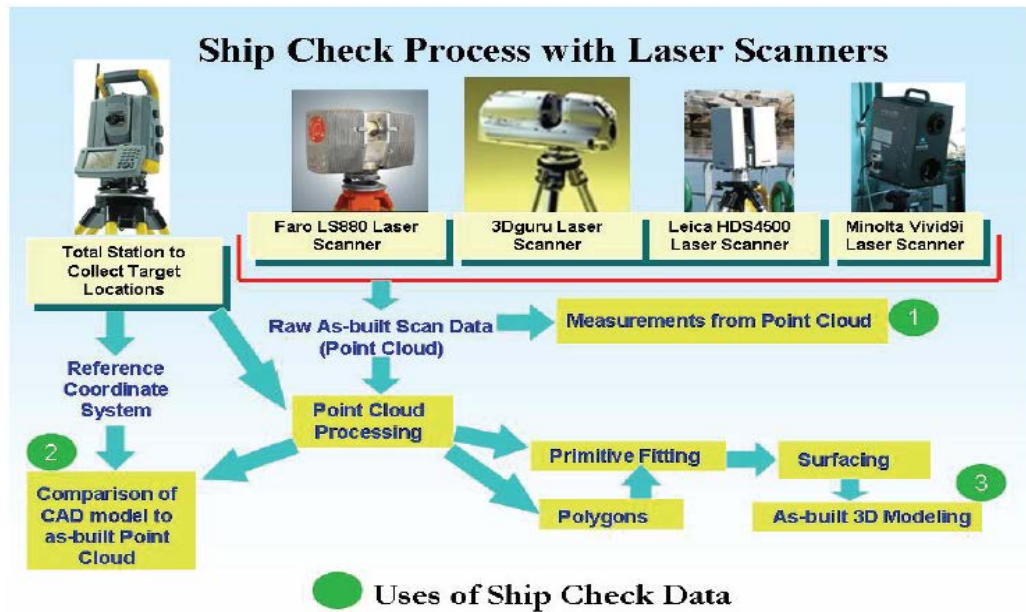
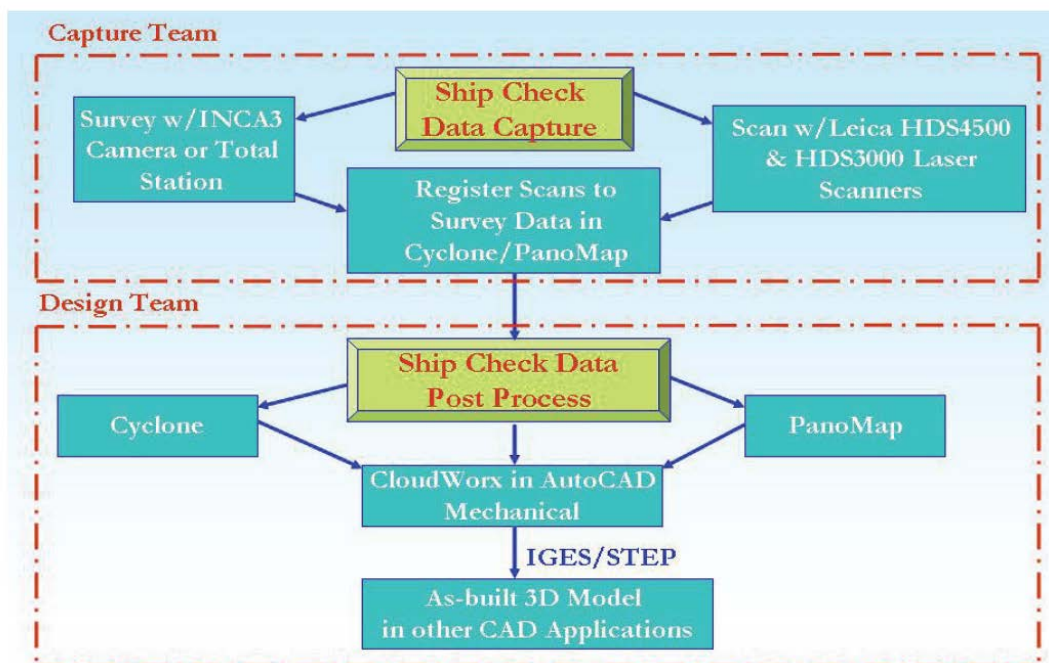


Figure 9. Flow Diagram: Ship Check Data Capture/Post Process (NSRP, 2007)



The project conclusions were that the technology (hardware/software) was mature enough to support the ship check process. Laser scanners were found to provide a cost-effective method of collecting as-built data during ship checks as compared to traditional methods. 3DLS provided time and cost savings, and can be applied to the shipbuilding industry.

The ship check process developed in these projects benefits the shipbuilding industry in several ways:

- Reduces or eliminates costly “return visits” to site for measurements normally missed using traditional ship check methods.
- Provides more accurate and complete as-built data for retrofit design projects, resulting in better retrofit designs, which ultimately results in cost savings and cost avoidance. With better designs, less construction rework is required (due to interference and fit-up problems and ability to factory-fabricate instead of having to field-fabricate).



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VI. 3D Scanning in the Navy

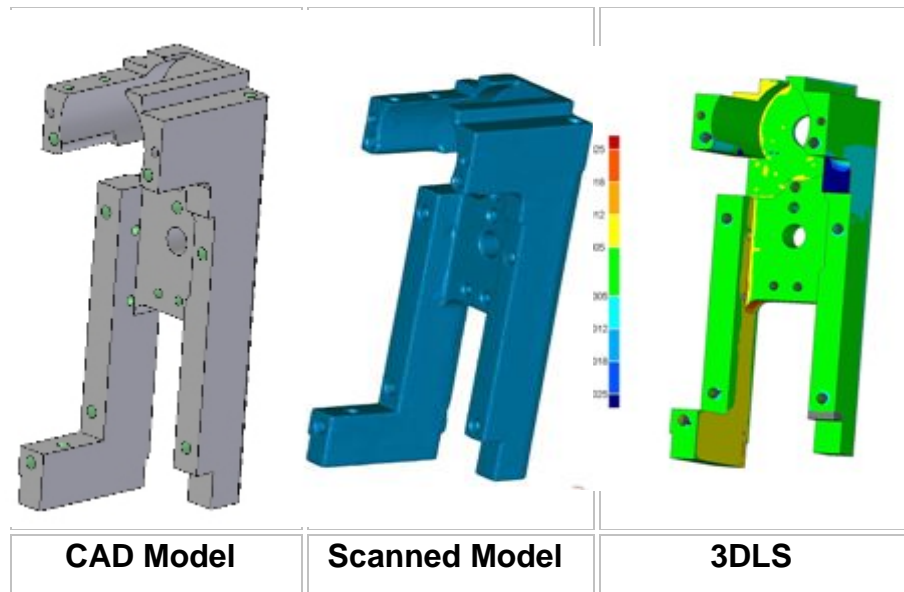
Naval Sea Systems Command (NAVSEA) deployed 3DLS to improve the efficiency of both shipcheck and shipalt processes in 2005. *Shipcheck* is the front-end capture and validation of dimensional data, equipment lists, maintenance records, and performance specifications used in shipalt. Traditionally done manually by labor-intensive and costly methods, shipchecks involved using measurement methods such as tape measures, plumb bobs, and spirit levels. *Shipalt* is the follow-on alterations, maintenance, and modernization of a vessel.

In 2005, 3DLS services were used for the shipcheck of a three-story hangar bay on the USS *Abraham Lincoln* (CVN 72). Scanning the HVAC, piping, fuel storage tanks, and other structures allowed shipyard engineers to conduct multi-discipline “what-if” scenarios to avoid clashes in the installation of a new deck. Hundreds of hours in labor were saved with scanning versus traditional methods. 3DLS captured data at up to 2000 points per second and has a range accuracy of 0.2 inches at 55 feet. 3DLS technology was used to assess damage to the USS *San Francisco* (SSN 711) after it collided at high speed with an undersea mountain 350 miles south of Guam. 3DLS was used to evaluate the damaged areas of the submarine’s bow. In this case, scanning was invaluable for determining the ship’s centerline and collecting empirical data about torpedo tube deformation.

The Naval Undersea Warfare Center (NUWC) began using laser scanning to reverse engineer components with complex geometries in order to enable competitive bidding in 2007 (see Figure 10). In the past, the Navy did not have sufficient documentation from the original equipment manufacturer (OEM) to competitively procure replacement components, which resulted in purchasing very expensive replacements from the OEM. The Navy saved \$250,000 by purchasing parts produced with laser scanning through competitive bidding. In addition, the time required to reverse engineer a typical component, including both measurement and modeling time, was reduced from 100 hours to 42 hours with a laser scanner.



Figure 10. CAD, Scanned, and 3DLS Comparisons



VII. 3D Laser Scanning in Shipbuilding

Shipbuilding is one of the most complex and demanding of the manufacturing industries, combining aspects of both direct product manufacturing and capital project development. Moreover, shipbuilders often face huge monetary penalties amounting to hundreds of thousands of dollars per day for being off schedule. 3DLS is a cost-effective, accurate, and fast method of helping shipbuilders and manufacturers design, redesign, modify, and salvage ships.

However, only a handful of several progressive shipyards (Meyer Wert GmbH, Signal International, and Babcock International) use laser scanning technology because it is not currently widely adopted by the shipbuilding industry. Meyer Wert GmbH, a shipbuilder from Papenburg, Germany, uses laser scanners to assist in building cruise liners, tankers, and ferries. New ships are constructed from over 60 individual sections called blocks, weighing up to 800 tons each (Leica Geosystems, 2015). Precise connection interfaces are critical in ship construction and block assembly; mistakes cannot be made, so consistent and accurate measurements are crucial. At every stage of new ship production, a surveying team using laser scanning technology provides services. With more ship parts being prefabricated and then attached to the ship in one piece, 3D surveys, such as taking the measurements of a sun shade composed of multiple concave shapes or a 260-m-long waterslide with curves and loops, are critical.

Signal International, a shipbuilder with multiple facilities in the U.S. Gulf Coast, uses a laser scanner on as-built models to check new production, as well as to generate CAD models for refit projects. It uses the technology to assist in the creation of

- accurate bill of materials
- general arrangements
- pipe arrangements
- pipe ISO's by system
- pipe spool drawings
- equipment details
- structural arrangement



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VIII. Additive Manufacturing

The American National Standards Institute (2013) defines *additive manufacturing* (AM) as the “process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies.” AM is also commonly referred to as 3D printing. AM differs radically from the currently dominant manufacturing methodologies. Most current methods use subtractive processes (e.g., machining), but AM builds a 3D object by gradually adding successive layers of material that are laid down exactly in their final location. AM does this by fabricating objects directly from 3D CAD models. The 3D model is disaggregated into multiple horizontal layers, each of which is produced by the machine and added to the preceding layers. AM is often referred to as 3D printing.

AM generally involves a number of steps that move from a virtual 3D CAD model to a physical 3D object, as follows:

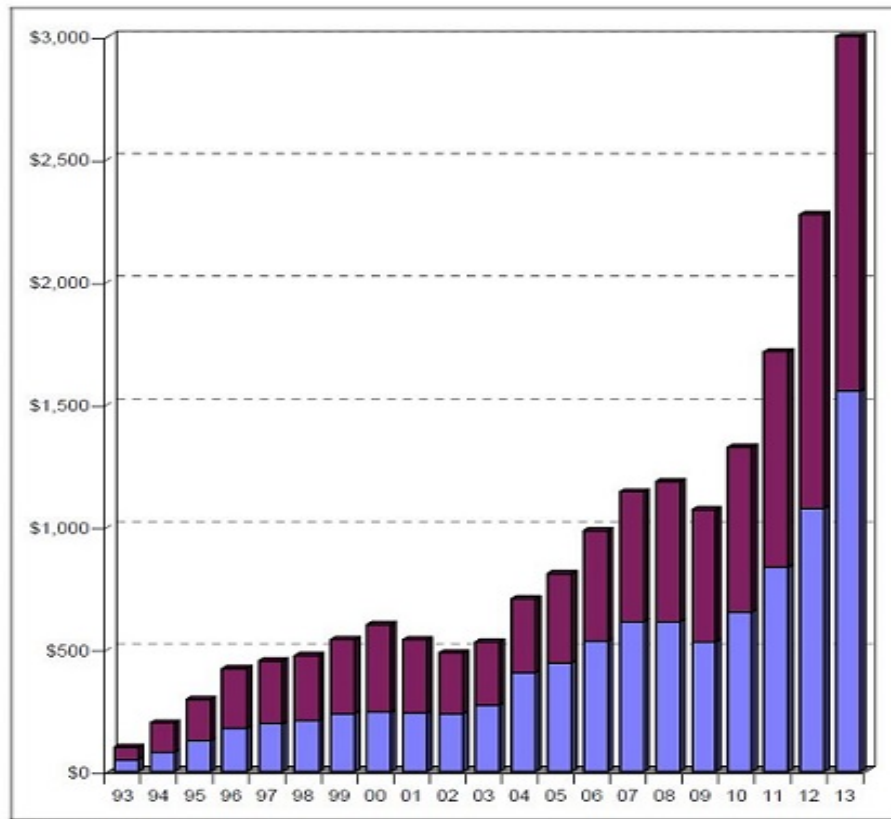
- **CAD:** A 3D CAD model of the target object is built in the software. The 3D CAD model determines only the geometry of the target object. 3D laser scanning can be used to create the model.
- **Conversion to Stereolithography STL files:** The CAD model cannot be used directly by AM machines; it must be converted to STL format. An *STL file* describes the external closed surfaces of the original CAD model and forms a basis for calculation of layers. The STL model approximates surfaces of the model with a series of triangular facets.
- **Revision of STL File:** STL files must often be manipulated before manufacturing. For example, multiple objects may be manufactured simultaneously from the same file, requiring that the STL files of the objects be integrated.
- **Machine Setup:** AM machines must be set up to accommodate specific materials, layer thicknesses, and timing.
- **Build:** Although all AM machines follow the layer-by-layer fabrication process, they utilize different techniques and technologies. For example, some of them use a high-power laser beam to melt a very fine metal powder in order to form a thin layer, while some others use UV light to solidify a specific kind of liquid polymer, called *photopolymer*.
- **Post-Process:** Post-processing may be required due to the need to cure photopolymers.



Additive manufacturing/3D printing is often referred to as a disruptive technology and promises to have profound ramifications for businesses all along the supply chain. Fueled by rapid technological developments, new applications, and falling costs, the 3D printer manufacturing industry has surged over the past five years. According to market research firm Wohlers Associates, the market for 3D printing, consisting of all products and services worldwide, grew to \$3.07 billion in 2013. The compound annual growth rate (CAGR) of 34.9% is the highest in 17 years. The growth of worldwide revenues over the past 26 years has averaged 27%. The CAGR for the past three years (2011–2013) was 32.3% (Wohlers, 2014). Figure 11 shows revenues (in millions of dollars) for AM products and services worldwide.



Figure 11. Additive Manufacturing Products and Services Revenues (Wohlers, 2014)



The first additive manufacturing system was created in the early 1980s when Charles Hull invented stereolithography (SLA), a printing process that enables a tangible 3D object to be created from digital data. The technology was then used to create a 3D model from a picture and allows users to test a design before investing in a larger manufacturing program. Since then, AM has evolved to include at least 13 different sub-technologies grouped into seven distinct process types. Figure 12 shows the evolution of AM technology. According to the Gartner Group (2014), consumer adoption of 3D laser printing will take over several years, as seen in Figure 13.

Figure 12. Evolution of Additive Manufacturing Technology 1985–2014 (Cotteleer et al, 2013)

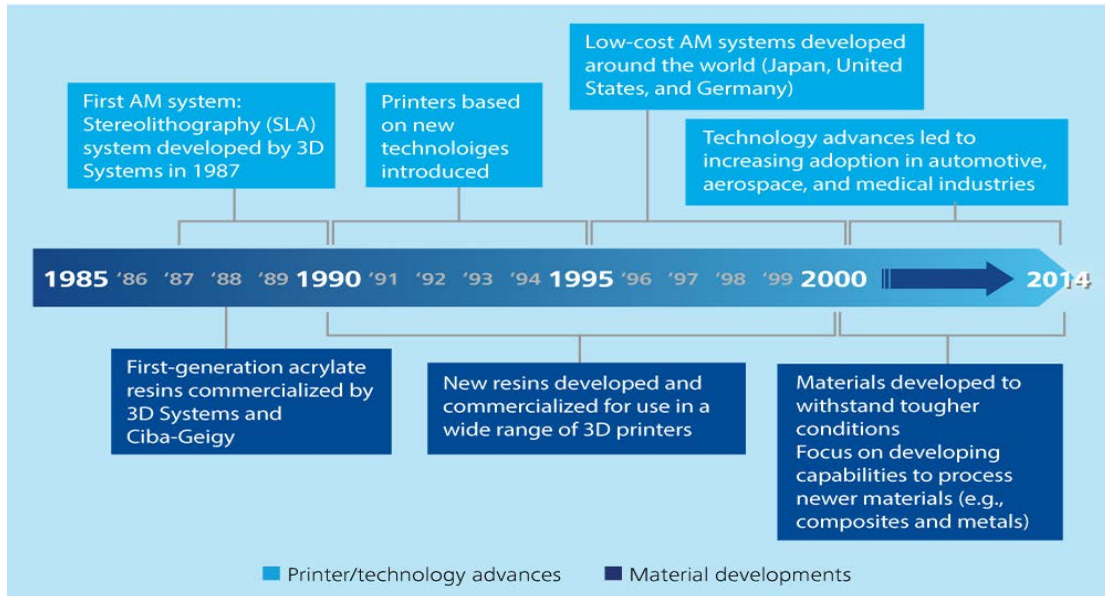
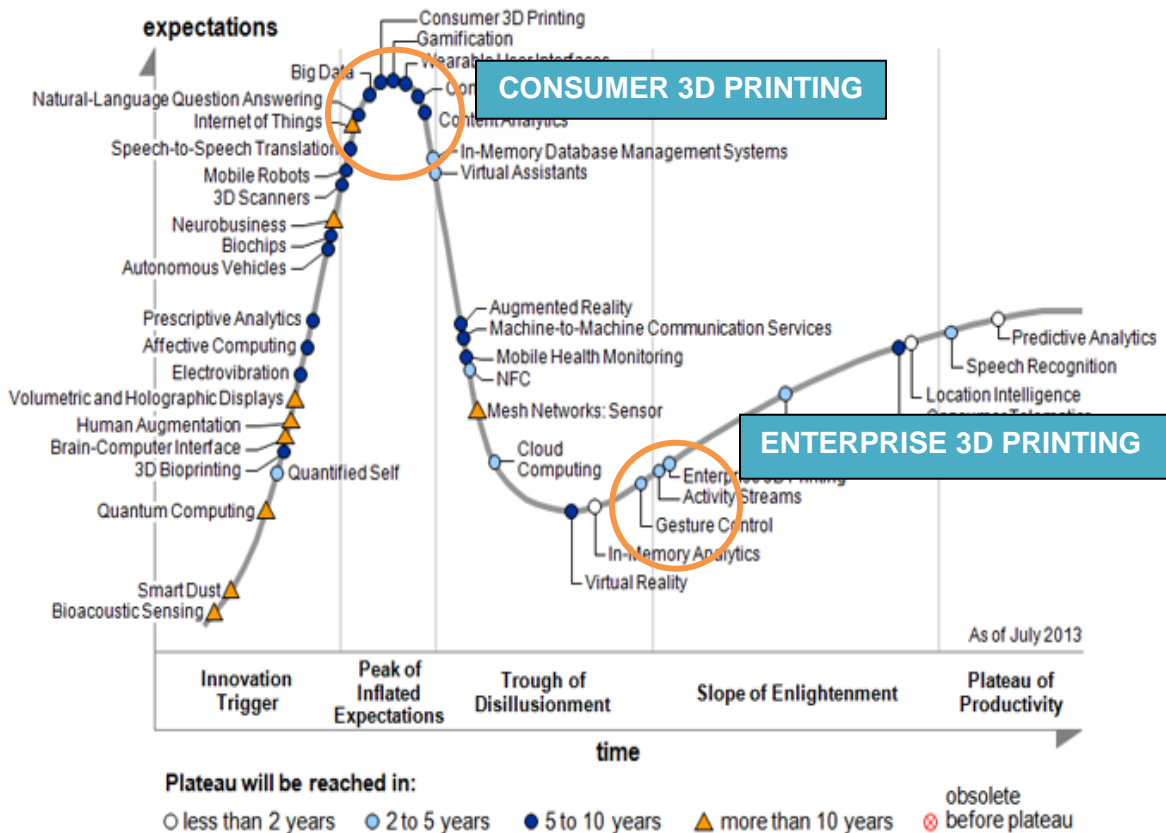


Figure 13. Gartner 3D Technology Hype Cycle (Gartner Group, 2013)



However, 3D printing is already a staple in many manufacturing processes and is being used more and more across a number of industries, including aviation, automobile, and healthcare. Lockheed Martin estimates that some complex satellite components can be produced 48% cheaper and 43% faster with 3DLS. Production costs could be reduced by as much as 80%. Boeing has been installing environmental control system ducting made by AM for its commercial and military aircraft for many years; tens of thousands of AM parts are flying on 16 different production aircraft (commercial and military; Caffrey and Wohlers, 2014). Airbus is also using 3D printing to produce a seat belt mold as a spare part for the A310 jet. Figure 14 is a 3D printed part by Airbus. GE Aviation will be using AM to manufacture more than 30,000 fuel nozzles annually for its new LEAP engine starting in 2015. Consolidating 18 parts into one, the new design is 25% lighter and five times more durable than the previous fuel nozzle.

Figure14. 3D Printed Part by Airbus (Siemens, 2014, p. 10)



In the automotive industry, Ford Motor Co. uses 3D printing in several areas, including the tooling used to create production parts and to build intake manifold prototypes that can be tested for up to 100,000-mile cycles. With traditional manufacturing methods, it would take four months and cost \$500,000 to build, while a 3D-printed manifold prototype costs \$3,000 to build over four days.

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IX. Additive Manufacturing in the Armed Forces

The U.S. Navy has supported research into 3D printing for more than 20 years and has approximately 70 AM projects underway at dozens of different locations. Figure 15 highlights AM maintenance projects, and Table 9 summarizes benefits achieved for several completed projects. In addition, one of the active Navy Manufacturing Technology (ManTech) Program projects active in FY2014 was the “Non-Destructive Inspection for Electron-Beam Additive Manufacturing of Titanium.” In this project, the emerging AM technology of the Electron Beam Direct Manufacturing (EBDM) process was evaluated for fabrication of several F-35 Joint Strike Fighter (JSF) components. EBDM is a technology that is considered vital to improving affordability, reducing lead time, and reducing industrial shortfalls inherent in traditional manufacturing technologies. In this Navy Metalworking Center (NMC) ManTech project, an integrated project team (IPT) evaluated the effectiveness of traditional and advanced non-destructive inspection (NDI) techniques, including computed tomography (CT) scanning, traditional radiography, standard hand-held ultrasonic, and phased array ultrasonic inspection methods, to establish standardized NDI processes and procedures for production. According to the Office of Naval Research (ONR), studies have shown that EBDM technology has the potential to reduce per-part manufacturing costs by 35 to 60% when compared to the costs of manufacturing complex-shaped parts with traditional manufacturing approaches (ONR, 2015). Product lead time might also be reduced by as much as 80%.

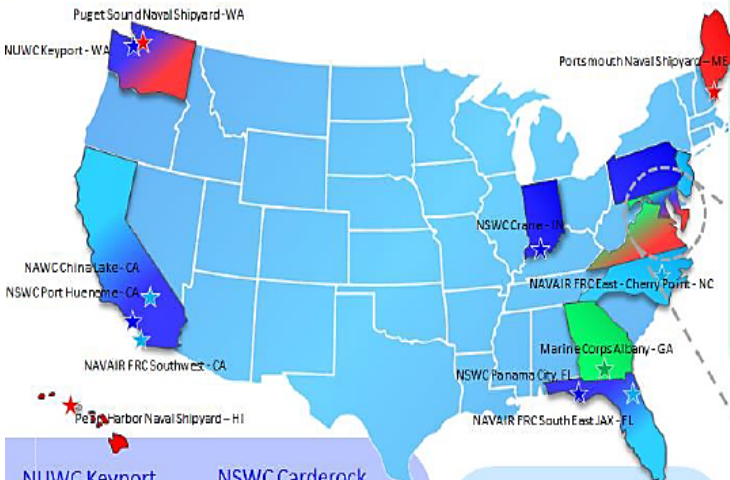


Figure 15. Additive Manufacturing in the Navy (Root, 2014, p. 1)

10/01/2013

Additive Manufacturing in the Navy

Shipyards NAVAIR NAVSEA Other Navy Activities



Naval Research Lab

- Micro-fabrication of electronic components
- Sensor/build integration
- New material research
- Microwave sintering
- In-situ characterization



Office of Naval Research

- STEM outreach
- Research programs


Walter Reed National Medical Center

- Custom medical tooling
- Prosthesis
- Cranial implants
- Surgical guides






NUWC Keyport

- Sand casting molds
- Rapid prototyping
- Metal repair
- End use parts



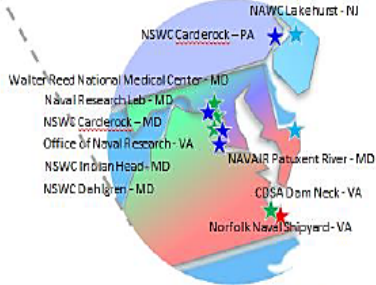
NSWC Carderock

- Ship models
- Seakeeping prototypes
- Working prototypes

NAVAIR FRC East

- Rapid prototyping
- Rapid tooling

NAWCLakehurst - NJ
NSWC Carderock - PA
Walter Reed National Medical Center - MD
Naval Research Lab - MD
NSWC Carderock - MD
Office of Naval Research - VA
NSWC Inish Head - MD
NSWC Dahlgren - MD
NAVAIR Patuxent River - MD
CDSA Dam Neck - VA
Norfolk Naval Shipyard - VA

NAWC China Lake

- Custom parts
- Rapid tooling

NAVAIR FRC Southwest

- Rapid prototyping
- Rapid tooling

NAVAIR FRC South East

- Rapid prototyping



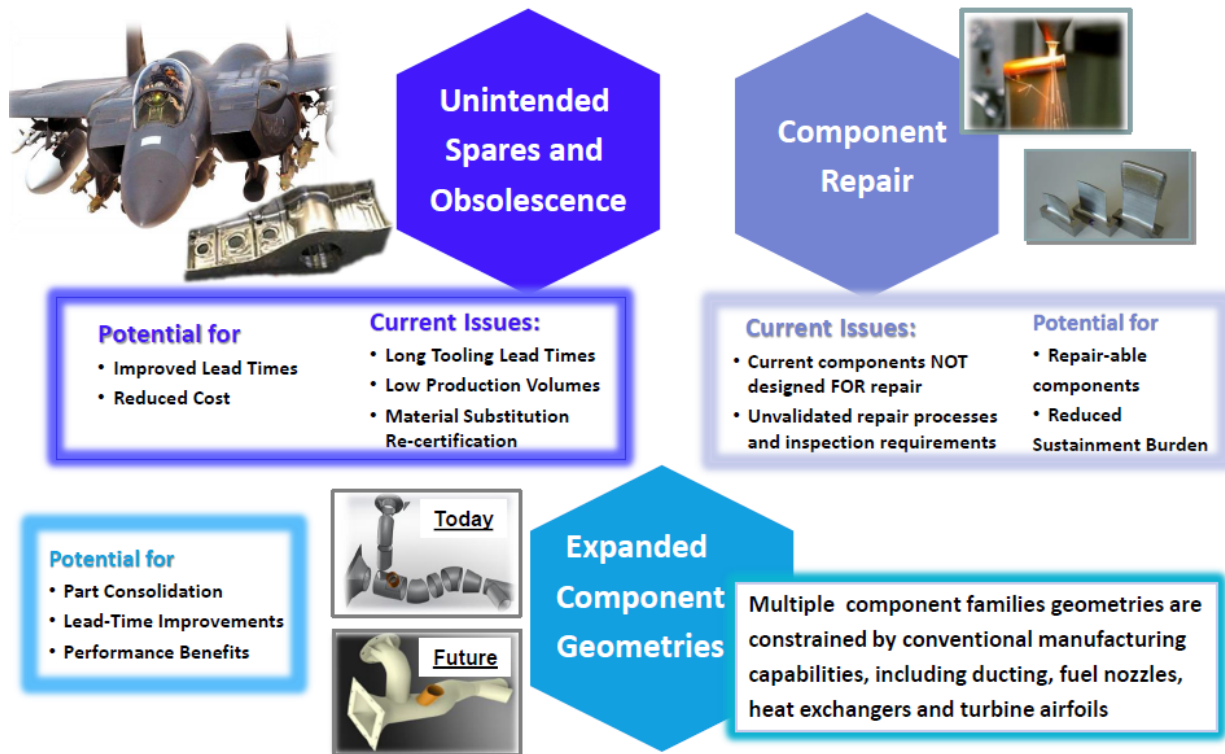
**Table 9. Additive Manufacturing Projects and Benefits
(Root, 2014; DoD ManTech Program, 2013)**

	Rapid Manufacturing & Repair: Casting Cores	RARE Parts Program: Part Vacuum Rotor Weapon System Submarines	ManTech Data Link Systems
Cost & Time Savings	\$4K & 4 weeks	\$20K & 30 weeks	<ul style="list-style-type: none"> Reduced unit cost of Mini Data Link Diplexer from ~\$20,000 to ~\$2,000 each Reduced lead time from 13 months to 3 months Approx. 65% cost savings
Problem/Challenge	<ul style="list-style-type: none"> Providing low quantity castings for fleet needs 	<ul style="list-style-type: none"> Vacuum rotor: Part can be hard to get Cost is \$19K, lead time 48 weeks 	<ul style="list-style-type: none"> Warfighter needs real time networked data in theater However, cost grows as bandwidths become more crowded Data link systems found in Unmanned Aerial Vehicles (e.g., Predator, Global Hawk, Hunter) are expensive, have long lead times due to exotic materials, and require extensive skilled labor with long cycle times
Solutions/Results	<ul style="list-style-type: none"> System for printing sand casting molds and cores: skips cost and lead time associated with making a pattern to pack sand around 	<ul style="list-style-type: none"> Part reverse engineered and CAD model created by TRF-King's Bay. Mold modeled at NUWC-Keyport, and mold will be poured by Naval Foundry & Propeller Center (NFPC) Printed mold using Ex One S15 system, cast parts at local foundry Cost \$14K, lead time 8 weeks 	<ul style="list-style-type: none"> Air Force ManTech developed and produced a tuneless diplexer using additive manufacturing to reduce material waste, cycle time, cost and to increase yield Utilized highly-developed software simulation and advanced manufacturing techniques to create Advanced Tuneless Diplexer that delivers superior performance at significantly reduced cost Implemented the following manufacturing improvements into new Mini Data Link product to improve overall data link lead time and cost: <ul style="list-style-type: none"> Replaced complex precision machined parts with inexpensive die cast components Eliminated gold plating, tuning and re-tuning Incorporated automated test to assess twenty units at a time AFRL ManTech investment of \$5.4M
Benefit/Impact	<ul style="list-style-type: none"> Costs: Slight cost decrease Time: Substantially reduces lead time Weapon system: Any system that uses castings 	<ul style="list-style-type: none"> Costs: \$20K savings per year based on 4 units annually Time: 30 week lead time reduction better suits emergent needs Weapon system: Vacuum/priming pump used on subs 	<ul style="list-style-type: none"> Provides warfighter with affordable, capable, real time networked data Increased performance and reliability of diplexer by reducing manufacturing variability



In July 2012, The U.S. Army deployed its first mobile 3D printing laboratory in Afghanistan inside a shipping container that is capable of being carried by helicopter. Figure 16 highlights how additive manufacturing can be used in maintenance activities.

Figure 16. Additive Manufacturing Aerospace Opportunities (Naguy, 2014, p. 3)



Additive Manufacturing in Naval Ship Building

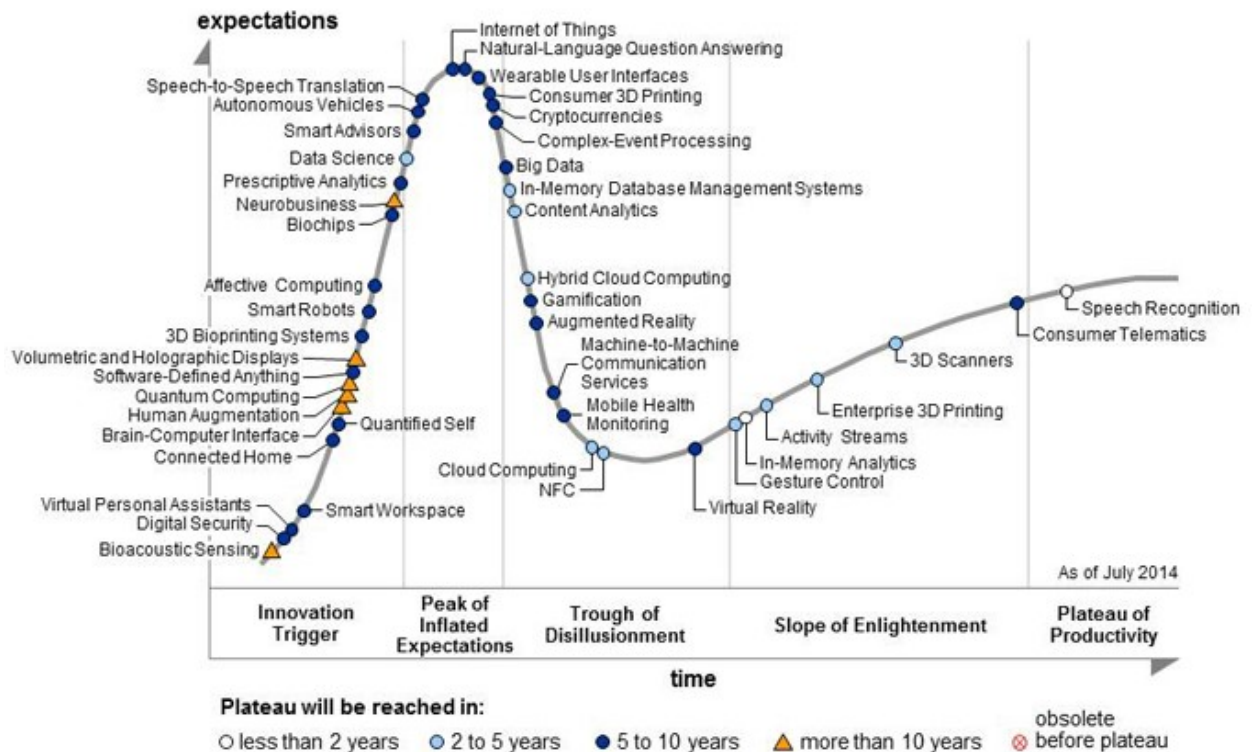
The Navy Metalworking Center (NMC) is conducting the Additive Manufacturing for Shipbuilding Applications project to demonstrate the cost and time benefits of AM to support the construction of Navy platforms. The project is investigating how the use of AM in ship construction can save acquisition costs on several ship classes. More specifically, Ingalls Shipbuilding (Ingalls) and the Integrated Project Team (IPT) will assess and demonstrate the use of AM during ship construction activities, quantify the expected benefits, and provide a recommended path toward implementation.

Ingalls has estimated a minimum acquisition cost savings of \$800,000 per year by utilizing AM for the construction of DDG, LHA, and LPD. Implementation at Ingalls is planned in FY2017 for DDG 121, LHA, and all future surface combatants produced there.

X. Summary

Traditional shipbuilding is an expensive and extensive process. PLM, 3DLST, and AM are technologies that have been applied in other industries to reduce costs and increase efficiencies, and have the potential to reduce naval shipbuilding costs. Prior research by the proposed research team indicated that using these technologies can save hundreds of millions of dollars in ship maintenance, suggesting that large savings in ship-building are also available. These technologies are past the disillusionment stage and are in the enlightenment phase where benefits are being derived, as seen in Figure 17.

Figure 17. Hype Cycle for Emerging Technologies (Gartner Group, 2014)



In this first phase of our study, we reviewed industry applications and tangible benefits resulting from PLM, 3DLS, and AM to understand the potential ramifications from these technologies. The next phase of the study will develop an assessment of the potential adoptions and use of these technologies for naval shipbuilding. That assessment will help decision-makers choose how much, when, and in what manner to exploit the benefits and minimize costs. Steps in that assessment include the simulation of shipbuilding processes, the impacts of the technologies on shipbuilding processes, and their attractiveness for use in shipbuilding. Simulating shipbuilding processes requires conceptual and formal models of shipbuilding. These will be



combined with estimates of technology impacts, and the two sets of simulations (pre- and post-technology adoption) will be used to model attractiveness. The knowledge-value-added (KVA) simulation approach will be used to model the return on investment (ROI) of shipbuilding with and without the three technologies. The resulting ROI will be compared to estimate the attractiveness of the technologies.

The simulations will also be the basis for evaluating implementation strategies. Specifically, we will be employing the integrated risk management (IRM) methodology, which includes approaches in Monte Carlo risk simulation, stochastic predictive modeling, KVA analysis, strategic real options and analysis of alternatives, and decision analytics, as well as portfolio optimization and resource allocation under constraints.



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