Final Report
NSRP ASE Ship Check Data Capture Follow-on Project (NSRP ASE 05-01)

March 7, 2007


Candies IMR **SSGN 729**

Participants

Electric Boat Corporation (Lead); Bender Shipbuilding & Repair Company; BitWyse Solutions, Inc.; Construction Systems Associates, Inc.; Direct Dimensions, Inc.; Faro Technologies, Inc.; Gulf Coast Region Maritime Technology Center; Photo Measurements Solutions, LLC.

Distribution

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Annexes

1. Executive Summary

- **Introduction:**

Electric Boat was awarded a FY06 follow-on ship check project by NSRP ASE to evaluate the FY05 ship check process further and provide a refined ship check process to the U.S. shipbuilding and repair industry using available (COTS) technology. Electric Boat has developed a ship check process based on the FY06 follow-on ship check project evaluations. The technology (hardware/software) is mature enough to support a digital ship check process. Phases I and II of the ship check project are now complete. This is the final report of the project, and its conclusions are based on the work accomplished under the two phases of this project.

The main report provides highlights of the ship check data capture project, Annexes A to H of this report provide a detailed overview of the ship check project, Annex–I provides the refined ship check process, and Annex–J provides a "Consumer Reports" like evaluation. Annex–J contains pros and cons of the hardware and software of the two data capture technologies (laser scanning and close range photogrammetry) evaluated under Phases I and II of the ship check project.

- **Work Summary:**

Two ship checks, onboard the Candies Inspection, Maintenance, and Repair (IMR) vessel at Bender Shipbuilding and onboard the SSGN 729 submarine in Norfolk, VA, were conducted successfully as planned during the 2nd and 3rd quarters of this project.

The lessons learned from the first ship check of Candies IMR were used in planning for the SSGN 729 ship check in order to improve the process in both the data capture and data processing techniques. The team learned more lessons during this second ship check. All of the lessons learned from the two ship checks under this project are included in this report.

The first ship check onboard the Candies IMR vessel at Bender Shipbuilding was done in five spaces (Bow, Engine Room, Moon Pool, Z-Drive Recess, and Pilot House), as well as the moon pool door and Z-Drives, using two laser scanners, a digital camera, and a video camera (only used for the pilot house for future processing with Vexcel Corporation's ImageOn software when this becomes available). The ship check of the pilot house was done only with a digital camera (for the close range photogrammetry process) and no laser scanners.

Two phase-based scanners (Faro LS 880, Z+F Imager 5003) were used for the Bender ship check and three phase-based scanners (Faro LS 880, Z+F Imager 5003, and 3Dguru) were used for the SSGN 729 ship check. All three of the scanners are relatively easy to use.

A Leica TDA5005A total station was also used to capture control points for registering the multiple scans to a single coordinate system for the ship check onboard the Candies IMR vessel at Bender Shipbuilding. An INCA3 8MPXL digital photogrammetry camera was used for the SSGN 729 ship check to capture control points for registering the multiple laser scans to a single coordinate system. The registration can also be done using identical features from each scan with COTS post processing software applications, but the use of the control points from the survey with a total station or a digital photogrammetry camera provides significantly more accurate results. The control points from the survey also speed up the alignment process and enable the scans from multiple spaces to be registered to a global coordinate system. The need for the survey should be based on the accuracy requirement of the collected as-built data.

Data analysis work of the Bender ship check was done at the participants' offices and the data analysis results were sent to EB to be included in the final report. Photo Measurements Solutions' (PMS) personnel were at EB to process a portion of the Bender ship check data using FotoG.

Data analysis work of the SSGN 729 ship check was done at Direct Dimensions in Baltimore, MD; at Construction Systems Associates in Atlanta, GA; and at the EB Business Lab in Groton, CT by Gulf Coast Region Maritime Technology Center (GCRMTC) personnel.

The close range non-targeted digital photogrammetry (FotoG) process with a digital camera (6 MPXL Nikon D70) was also used for the Bender ship check. The FotoG process, like total stations, if used in tandem with the laser scanner, has the potential to assist in accurately linking multiple scans. This will avoid the use of the troublesome "best fit" routines in the laser scan data post processing software. This concept still needs to be further evaluated.

- **Conclusions:**

The following are brief conclusions of the ship check data capture project (detailed conclusions are provided in Section 10 of this report):

- The technology (hardware/software) is mature enough to support the ship check process. Laser scanners provide a cost effective method to collect as-built data during ship checks as compared to traditional methods. Laser scanning technology will collect as-built data in a manner which will provide time and cost savings to the shipbuilding industry. The next steps of implementation of ship checks with data capture technology are up to the shipyards.
- The ship check data capture follow-on project resolved the remaining issues from the FY05 ship check project. The results are included in this report and are summarized as follows:
  - The follow-on ship check project confirmed the necessity of conducting a survey during the ship checks to merge the scans accurately.
  - The scan data measurements from the scanner being used to collect the data during the ship check need to be validated on-site during the first use of a scanner.
  - Field verification of completeness of data collection before leaving the ship check site with the use of a software application like Cyclone is a must to eliminate return visits to the ship.
  - The data analyzed and processed from the 3Dguru, Faro LS 880, and Z+F Imager 5003 (Leica HDS4500 is identical) laser scanners from the ship checks of this project is accurate within the desired tolerance of +/-3/16" on the as-built measurements of components.
- The benefits of conducting ship checks using the data capture technology are: 1) Creation of as-built 3D models and validation of as-built models to design models; 2) Reduction of costly design changes and improved design capability; 3) Reduced construction rework; 4) Accurate and less costly factory-fabricate in lieu of field-fabricate; 5) Reduced ship check costs: fewer days, fewer personnel; 6) Elimination of return visits to the site to obtain measurements of missed data which can happen with traditional ship check methods; 7) Obtaining measurements which are difficult or unsafe for human reach; 8) Scan data (point clouds and associated models) that is readily transferred between computer systems using standard methods such as IGES, STEP, STL, and DXF.
- The demonstrated uses of scan data from the ship checks are: 1) Creating 3D as-built models of the entire space (not cost effective at present), 2) Taking measurements (requires experience), 3) Validating 3D CAD models to as-built data by overlaying as-design or new design CAD model onto point cloud to check placement of components and interferences (cost effective), 4) Creating 3D as-built arrangements by placing library CAD model parts on location using the scan data (cost effective), and 5) Creating surface models for visualization and analysis (cost effective).
- The photogrammetry (FotoG) process may be able to be used to complement the laser scanning technology process. The generation of a usable CAD model from FotoG is a manual and difficult process. The combination of these two technologies may speed up the modeling process and also validate the data collection from each of the two processes. A complete evaluation on the synergy between these two technologies is beyond the scope of this project. It is, however, highly recommended that such an evaluation be accomplished by shipyards and NSRP in the future.
- A significant vendor network exists to support ship checks with data capture and post processing efforts. Shipyards should consider using vendor services for ship checks to assist them in their initial use of this technology.
- Traditional ship checks are still needed for some measurements which cannot be obtained by the data capture technology.

2. Project Overview

2.1 Objective

The overall objective of this project was to refine the ship check process developed under the NSRP ASE FY05 Ship Check Data Capture Project. In addition, the objectives of both Ship Check Data Capture projects were: 1) to develop a process that captures the as-built measurement data in digital/electronic format during a ship check; 2) to process the as-built measurement data into 3D CAD models using available commercial-off-the-shelf (COTS) modeling technologies (software and hardware); and 3) to ultimately 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.

The refined ship check process was intended to provide cost savings as compared to traditional ship checks using manual methods. The process was also intended to provide a cost effective method to create as-built 3D CAD models for new construction. During the course of this project, the project 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 FY05 project. The close range photogrammetry (FotoG) process with the digital camera was included only for the ship check at Bender Shipbuilding. The ship check data capture process investigated and developed through this project is focused on providing acquisition and lifecycle cost relief to the government through the generation and management of accurate 3D CAD models of as-built space and geometric measurement data.

2.2 Description

This project was awarded by the National Shipbuilding Research Program (NSRP) on April 3, 2006 as a nine month project. The participants were Electric Boat Corporation (Lead); Bender Shipbuilding & Repair Company; BitWyse Solutions, Inc.; Construction Systems Associates, Inc.; Direct Dimensions Inc.; Faro Technologies, Inc.; GCRMTC; and Photo Measurements Solutions, LLC. Technical Lead for this project was Raj Thiyagarajan; the Project Manager was Ken Peters, both from Electric Boat Corporation. The project entailed the evaluation of new technology data capture hardware and point cloud data post processing software as they apply to the U.S. shipbuilding industry. Electric Boat Corporation, Bender Shipbuilding, and GCRMTC are closely associated with the shipbuilding industry and, as such, have provided the project with the industry focused consultations, evaluations, and recommendations found herein. The service providers (BitWyse Solutions, Construction Systems Associates, Direct Dimensions, Faro Technologies, and Photo Measurements Solutions) brought their technology, products, and associated expertise to this project.

During the course of the project, two ship checks and the subsequent data processing were conducted, Candies IMR in the project's second quarter and the SSGN 729 in the third quarter. This follow-on project used two LIDAR laser scanners (Faro LS 880 and Z+F Imager 5003) for the Bender ship check and three LIDAR laser scanners (Faro LS 880, Z+F Imager 5003, and 3Dguru) for the SSGN729 ship check. A Nikon D70 6 MPXL digital camera was used to capture the as-built geometry in digital format to use in the FotoG close range non-targeted digital photogrammetry process (Bender ship check only). A Leica TDA5005A total station was used for the Bender ship check and an INCA3 8MPXL digital photogrammetry camera was used for the SSGN 729 ship check for the survey of control points used for registration of multiple scans into a single coordinate system.

The data processing and reporting for the Candies IMR vessel ship check were performed at EB facilities in Groton, CT and at the project participants' respective offices. The data processing and reporting for the SSGN 729 were performed at the EB facilities and at Direct Dimensions and Construction Systems Associates offices with Electric Boat (EB) personnel in attendance at all times during the post processing. At the project participants' offices the data was stored and processed using portable hard drives supplied by EB in order to comply with International Traffic in Arm Regulations (ITAR) restrictions. The collected data was processed using the following COTS software applications: PanoMap, PolyWorks, RapidForm, Imageware, Cyclone 5.3, LaserGen, CloudWorx, FotoG, and Spatial Analyzer. The techniques, lessons learned, and even specific events from the Bender ship check and data processing event were brought forward into the SSGN 729 event to provide repeatability and process validation. Timing studies as well as the accuracy of the results were monitored to provide the quantitative basis for findings. The validated processes and lessons learned are set forth herein. Data collected from the Candies IMR vessel from the Bender ship check has been authorized for public release.

A demonstration/presentation of this ship check project was given during the NSRP Panel Meetings on December 13, 2006 in Savannah, GA. The project participants working on this project were present at this event, discussing the hardware and software products used in this project. See Annex–A for Definitions, Acronyms, and Non-Typical Words in General. See Annex–B for Project Plan and Annex–C for Technology Introduction/Technologies to Evaluate/Technology Progress.

3. <u>Ship Check Data Capture</u>

Ship check data capture involves planning in advance the areas to be ship checked. The laser scanner locations from which each individual scan is taken need to be noted on the map of areas of the ship. Figure 1 is an example of the map for the scanner locations. This map helps during the post processing of the laser scan data. Also, the scans need to be taken at higher and lower elevations and at closer/farther distances from the bulkhead as shown in Figure 1, to achieve a complete line of sight of components which will provide complete data coverage of the space for measurements and 3D modeling of as-built spaces. See Annex–F for more information on data capture.

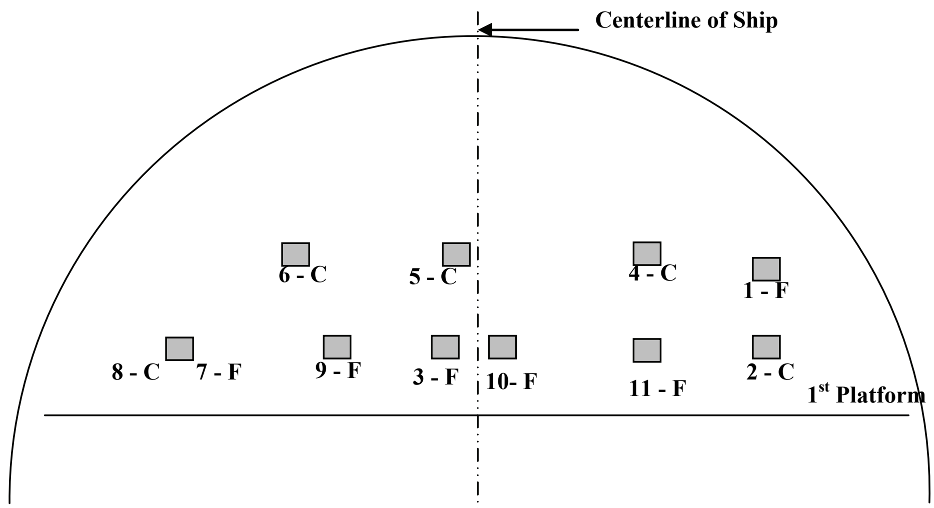

Figure 1:
Typical Scanner Location Map – SSGN Bulkhead
Scans 1 – 11: C is Closer to Bulkhead and F is Farther away from Bulkhead

The follow-on ship check project team has developed a refined ship check process (See Section 6) to capture as-built ship conditions and post process the data into meaningful, accurate information from the ship check data captured aboard the following vessels:

1. The project team used phase-based 3D laser scanners and the close range photogrammetry (FotoG) process with digital cameras to capture as-built data onboard a surface ship at Bender Shipbuilding and also performed a survey using a total station. The project team captured data at several locations using these two technologies and processed the data using various software applications (PolyWorks, Raindrop, Cyclone 5.3, LASERGen, FotoG, etc.). Data processing was done in the field during the data capture, at the service providers' sites, and at Electric Boat in Groton, CT. Time studies of these processes were performed along with tracking of the accuracy of data captured.

The Bender ship check and post processing provided answers to the following questions and helped the refinement of the ship check process:

- Is validation of scanner calibration required in field after the first scan is complete? (yes)
- Is a survey required to be performed in conjunction with a ship check? (yes)
- Can scans be merged based on features visible in the point cloud or are targets required? (targets are required)
- Is photogrammetry desired to be used in conjunction with laser scanning? (possibly)

2. The data capture onboard the SSGN 729 Bulkhead 51 (1st Platform) was done using the similar phase-based 3D laser scanners used under the FY05 project. No digital photogrammetry was performed onboard the SSGN. A minimal amount of post processing was done from the data collected from SSGN. The reasons for this trip were:
   a. Accuracy – confirm reasons for out of tolerance measurements on the initial ship check (FY05) and provide ways to mitigate
   b. Repeatability – take scans in the same locations as 2005 ship check, overlay 2005 data onto 2006 data, and compare
   c. Completeness – take enough scans in the same area as in 2005 to be able to complete modeling efforts that could not be completed in 2005 due to lack of adequate coverage of selected components

3.1 Survey

The follow-on ship check project used a Leica TDA5005A total station for the Candies IMR ship check survey at Bender Shipbuilding, Mobile, AL. The survey team placed a series of targets on the stern, baseline, and the bow of the Candies IMR vessel to accurately define the shape. This allowed the ship's coordinate system to be developed. Electric Boat used an INCA3 8MPXL photogrammetric camera during the SSGN 729 ship check in Norfolk, VA., to collect the data measurements in order to validate the SSGN 729 Bulkhead 51 component measurements (See Table 2 of Annex–H). The goal for the survey was to provide a baseline dimensional control set of points for multiple laser scans alignment from the ship check. The survey during the ship check is vital to align the scans from a laser scanner and the digital images for the FotoG process to a) speed up the aligning process and b) to build accurate as-built 3D models. Also, during this project evaluation, EB optical tooling personnel developed a swappable targeting scheme to collect LIDAR target data as well as the photogrammetry target data measurements that enables uninterrupted LIDAR/survey operations during the ship check. This means that the survey can be done in a space before or after the scanning is done as long as the swappable target bases are placed in the required locations as needed for the survey and not disturbed. See Annex–D for additional information on the survey done under this project.

3.2 Ship Check with Close Range Photogrammetry

The photogrammetry (FotoG) process for the Bender ship check used a Nikon D70 6MPXL camera with a calibrated focal length. This system attaches the focal length to the digital photograph as a readable data attribute. This process also uses a National Institute of Standards and Technology (NIST) traceable scale cross bar (1 meter) to calibrate the camera. See Annex–E for complete details on the FotoG process done under this project. All of the spaces onboard Candies IMR vessel as shown in Figure 2 except for the starboard side of the Bow Thruster Recess, Anchor Pocket, and Z-Drive recess were ship checked using the digital camera for FotoG process.

3.3 Ship Check with Laser Scanners

The first ship check onboard a 280 ft. Inspection, Maintenance and Repair (Candies IMR) vessel being constructed at Bender Shipbuilding in Mobile, AL using two phase-based laser scanners (Faro LS 880 and Z+F Imager 5003) was conducted on May 3 – 5, 2006. Data collected aboard is approved for public release (distribution unlimited). The following spaces (Figure 2, spaces 1-7) were ship checked onboard the Candies IMR vessel:

- Bow thruster recesses (Port and Starboard)/Anchor pockets (Port and Starboard) – (1,2)
- Moon pool/Door fit-up (3,4)
- Z-drive Recesses (Port and Starboard) and Z-drives (Port and Starboard) – (5,6)
- Engine room bulkhead (7)
- Pilot House (8) – No laser scanning, only FotoG process was used to collect data (See Section 3.2)

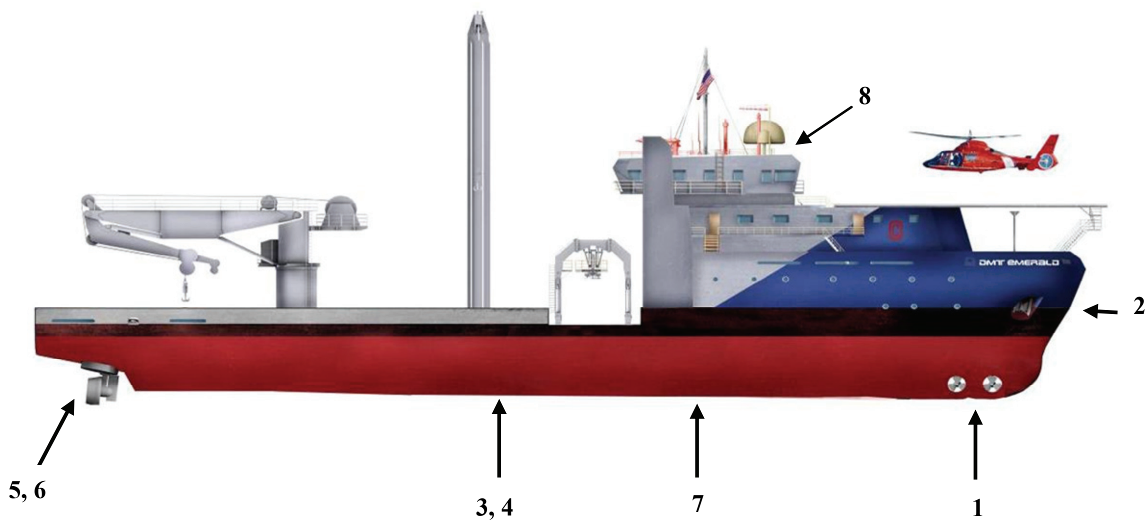

Figure 2:
Candies Inspection Maintenance & Repair (IMR) Ship Check Spaces (1-8)

The second and final ship check for this project using three phase-based laser scanners (Faro LS 880, 3Dguru, and Z+F Imager 5003) was onboard the SSGN 729 submarine in Norfolk, VA. It was conducted on June 26 – 28, 2006. Scanning of Bulkhead 51 (Missile Compartment 1st Platform) onboard the SSGN 729 was conducted to check the data accuracy. Scan data validation was done by placing 1-1/2"Ø spherical targets, BitWyse paper targets (2"x 2", w/1" blue/white squares), and NIST scale bars with Mensi target spheres at each end placed on the bulkhead, and photogrammetry measurements of these targets using INCA3 camera to validate scan measurements. The SSGN 729 ship check data was used to perform data measurement analysis which can be seen in Annex–H. See Annex–F for more information on ship check data capture with laser scanners.

4. <u>Ship Check Data Post Process</u>

The ship check data post processing was done under this project a) to take measurements of components, b) to verify as-built data to the design, and c) to create as-built 3D CAD model. Measurements as shown in Figure 3 were obtained from the merged scans (post processed point cloud data) of Candies IMR engine room taken from several locations. Simple measurements can also be obtained directly from the raw scan data as shown in Figure 4. As-design CAD model verification was accomplished by overlaying the point cloud on the design CAD model as shown in Figure 5. Primitive CAD models from the point cloud data were created and extrapolated into final CAD model as shown in Figures 6 and 7. See Annex–G for post processing of scan data of Candies IMR vessel and SSGN 729 ship checks.

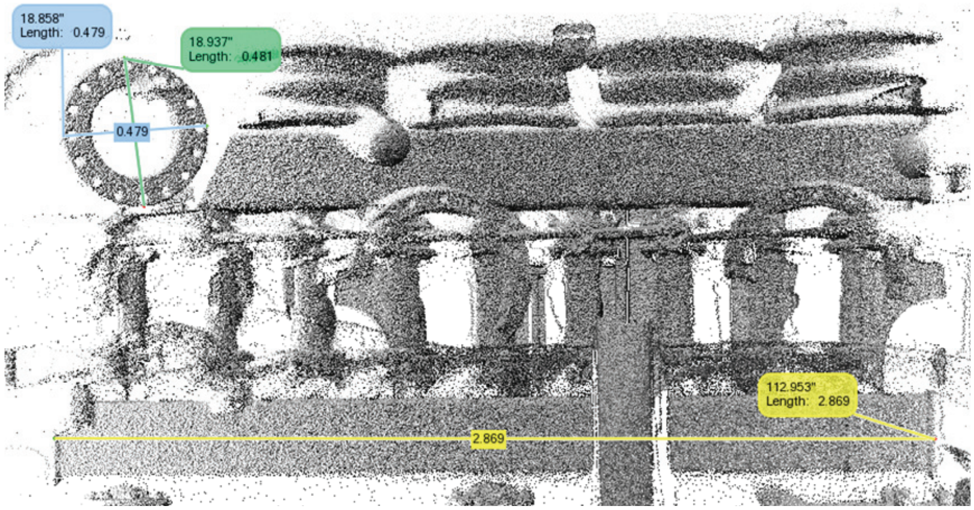

Figure 3:
Direct Measurements from Post Processed Point Cloud
(Candies IMR Engine Room Scan Data) in PolyWorks

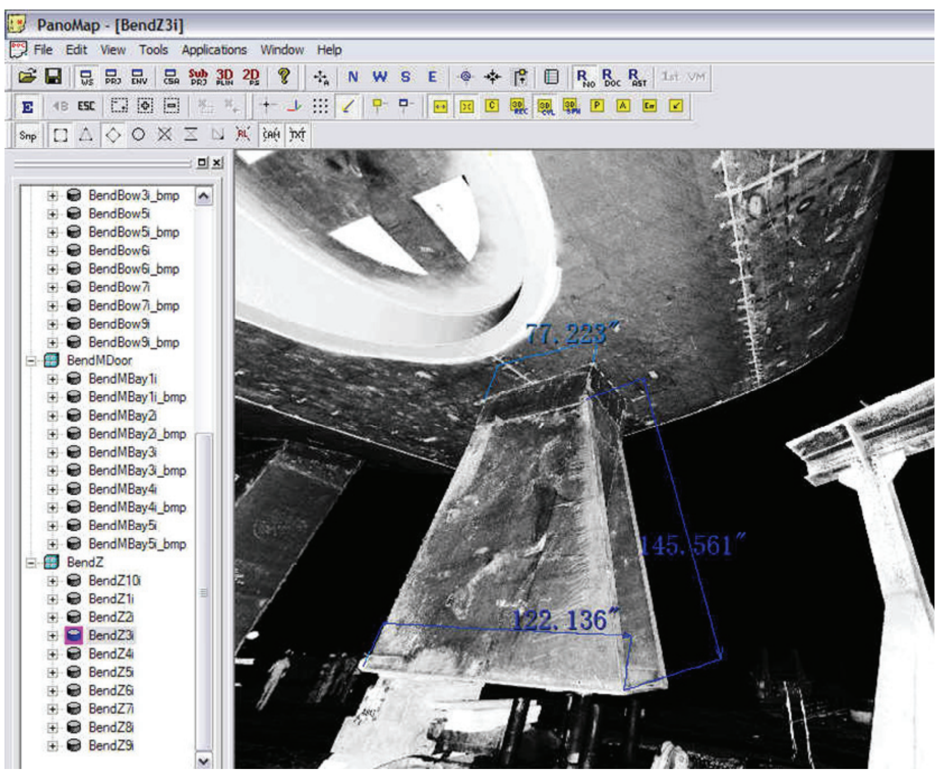

Figure 4:
Direct Measurements from Point Cloud (Candies IMR Stern Scan Data) in PanoMap

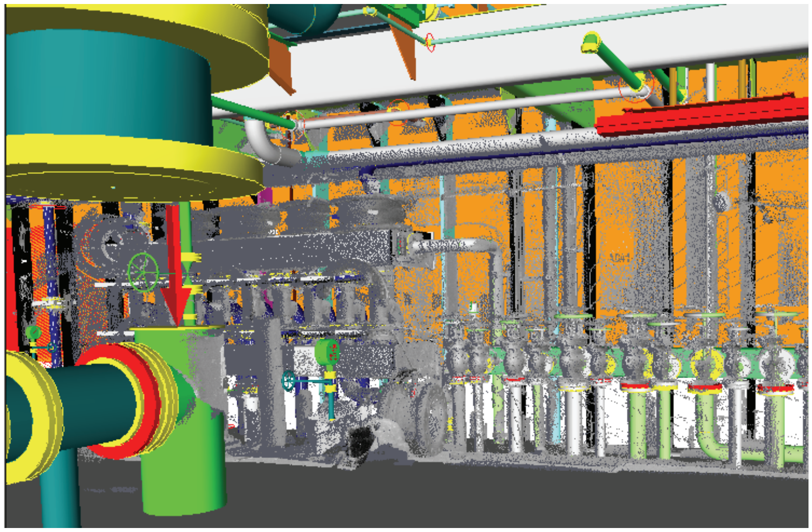

Figure 5:
CAD Model Overlay on the Point Cloud (Scan Data) for Design Verification

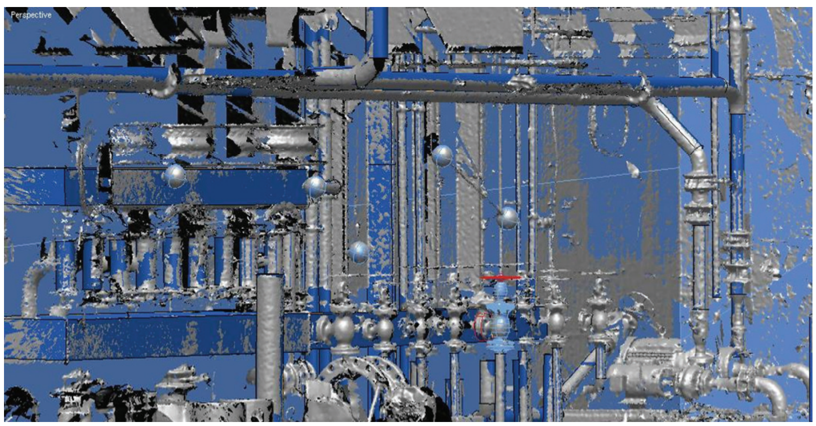

Figure 6:
Creation of Primitives from Point Cloud (Scan Data)

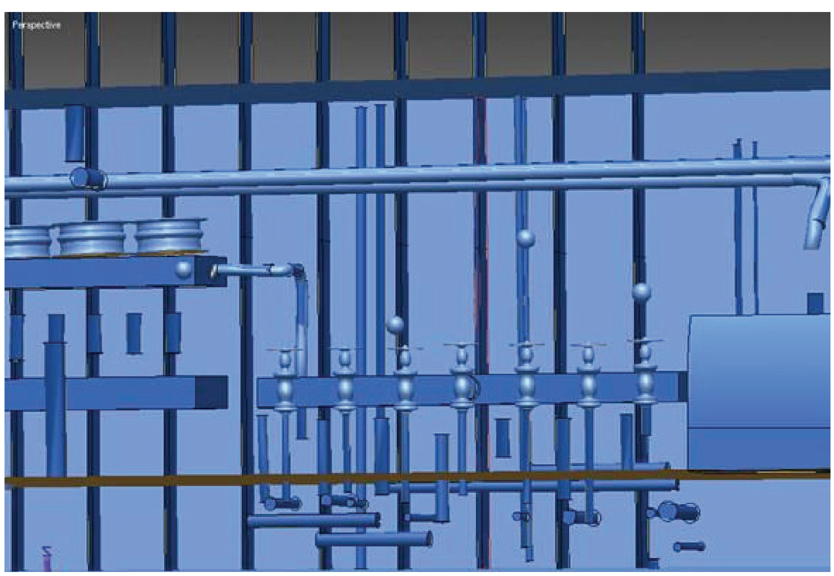

Figure 7:
Final CAD Model Extrapolated from the Primitives

5. Ship Check Data Analysis

The data analysis/modeling efforts of the Candies IMR ship check data were completed by the project participants using several post processing software applications. Direct Dimensions and Construction Systems Associates worked with EB participants with the scan and photogrammetry data from SSGN 729 to analyze the data measurements from all three phase-based scanners. Annex–H provides the ship check data analysis of both the Bender ship check and the SSGN 729 ship check.

5.1 Data Measurements

The post processed ship check data of Bulkhead 51 (1st Platform) from the Faro LS 880, Z+F Imager 5003, and 3Dguru laser scanners were analyzed and compared with measurements of components using a photogrammetry camera on-site, and the results are provided in Annex–H. Also, measurements of Candies IMR vessel's engine room bulkhead components were taken using a measuring tape and a total station. Annex–H provides the results of the measurements taken from the scan data from both the Candies IMR vessel and SSGN 729.

- Measurements of components from both ship checks (Candies IMR and SSGN 729) were found to be within the desired tolerance of +/-3/16".
- During the analysis of Faro scan data of the Candies IMR engine room, it was found that the Faro LS 880 laser scanner was not calibrated for close range data capture. The scanning vendor had to correct the scan data with a correction factor. The lesson learned from this is to verify the scan data measurement on-site after the first scan is completed.

6. Ship Check Process

The ship check process provided in Annex–I, is based on the evaluations of the laser scanning and close range photogrammetry technologies under the FY05 ship check project and this follow-on project. This process is a guidance tool and not to be considered as a definite solution for future ship checks. This process can be modified to suit the shipyard applications and needs and to suit technology advancements. Figure 8 shows the ship check process with laser scanners and shows the uses of ship check data, and Figure 9 shows a flow diagram of the ship check data capture/post process. See Annex–I for the complete ship check process which outlines the design/capture team for ship check, software/hardware needed, and a ship check procedure (work method).

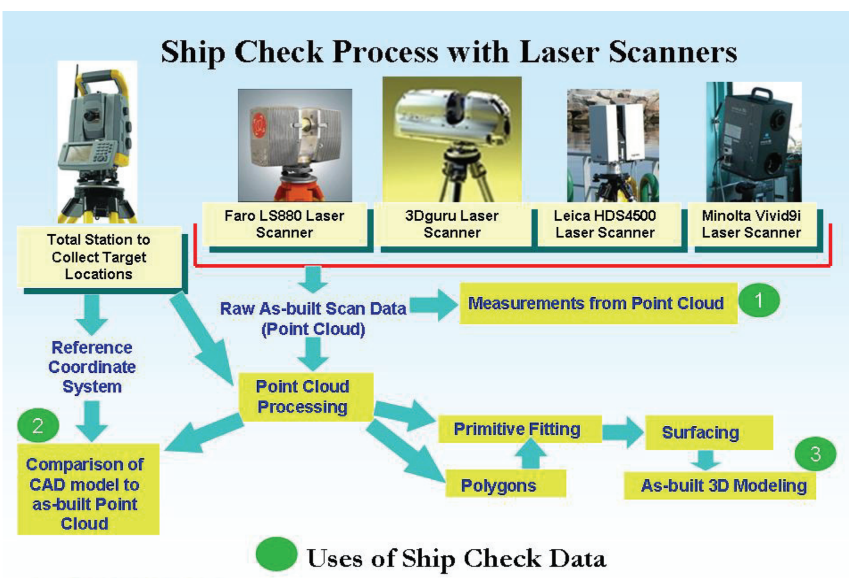

Figure 8:
Ship Check Process with Laser Scanners and Uses of Ship Check Data

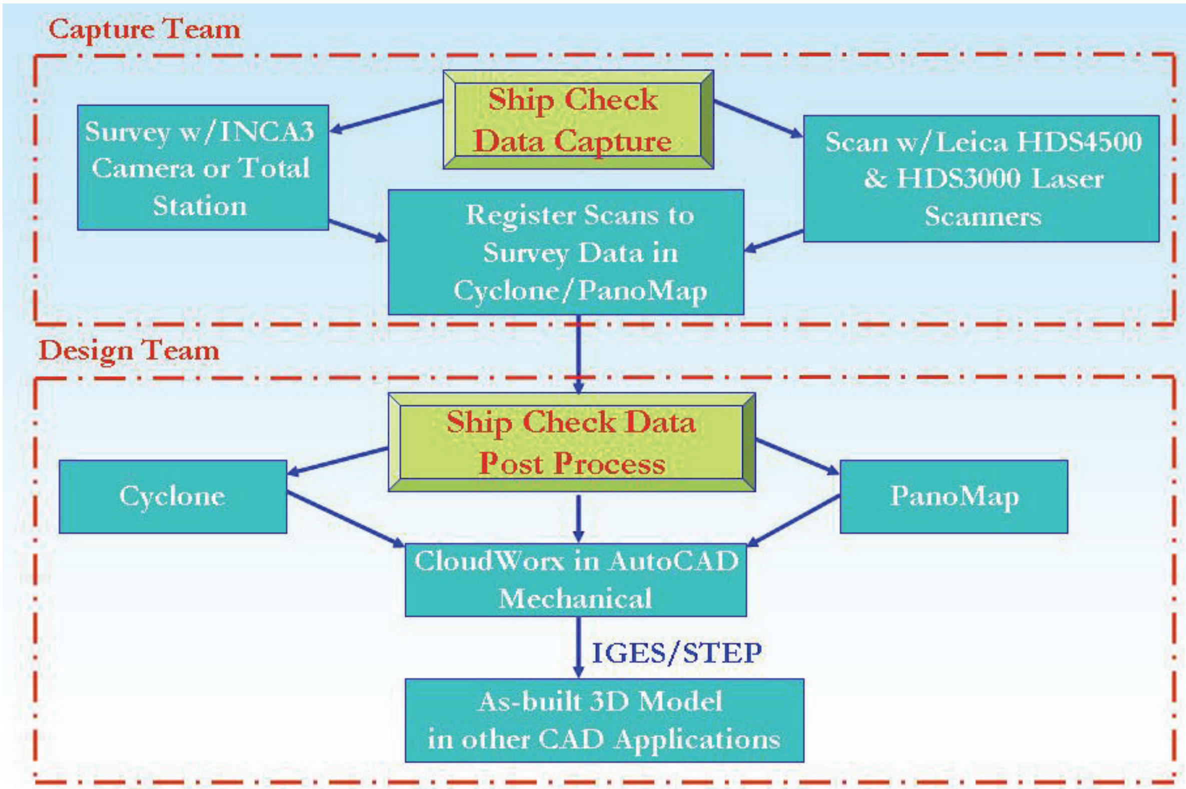

Figure 9:
Flow Diagram – Ship Check Data Capture/Post Process

7. Lessons Learned

Phase I and Phase II of the NSRP ship check project used available COTS laser scanning, photogrammetry, and survey hardware and software to collect as-built data during ship checks in digital format and to post process the data into 3D CAD models. The lessons learned under the ship check project evaluations are summarized as follows:

- Data capture work methods are critical for accurate/complete data collection and for accurate modeling of the as-built configuration of the components during the ship check.
  - Data collected needs to be validated on-site during the first use of a scanner with standard scale bars or a survey with control points.
  - Multiple scans must be acquired from various points of view for complete data capture.
    - Areas of interest may be missed due to excessive shadowing
    - Proper planning of scanner positions will help reduce this problem
  - Conducting a survey is critical to speed up the alignment of multiple scans and digital images (FotoG process) and to provide accurate modeling of as-built data.
- Advance planning is critical to assure a successful ship check:
  - The site should be visited prior to the ship check to plan scanning locations and resolve any logistics questions.
  - Any security issues need to be resolved as early as possible. This includes personnel access, equipment use, and equipment prohibitions.
  - Onsite storage of equipment aboard the ship at the end of shifts will considerably reduce ship check time by eliminating loading and removal of equipment during each shift.
  - Coordinate with ship's personnel to schedule the shift for data capture activities and make sure the ship check space will be clear of ship's crew since they may obstruct scanner operation.

- A map of ship check spaces and specific detailed requirements for the ship check planned prior to the ship check will speed up the ship check process.
- Since the submarine had only shore power, the team needed extension cords along with pigtails for adaptation to proprietary shore power systems. It was very hard to get the pigtails since the shipyard had limited quantity in supply and most of them were in use.
- A check-off list of required equipment, as noted below, should be completed prior to leaving for the ship check. This will eliminate the need for searching for equipment forgotten or not available during the ship check:
  - Extension cords
  - Pig tails
  - Power supply
  - Battery supply
  - Surge protector
  - Tripod

- Having the software application to merge all scans on-site to verify completeness of the data collection of the ship check space will improve the quality of the ship check. The reason for this is that during the post processing of the scans it might be found that there are shadows, reflective objects, or some component data missing due to overlap issue of the scans. All these issues can be resolved on-site during the ship check. For instance, the shadows can be eliminated with more scans at different elevations and/or closely spaced to provide more overlap of scan data.
- There are various factors affecting the quality of data collection with phase-based scanners which are noted, along with possible resolutions, below:

a) Lighting condition – Too much light is not acceptable (Need to be turned off or covered).

b) Shadows – Need to be resolved by taking more scans at different heights and at closer distances.

c) Edge effects – need to be rectified by the scanner software. The edge effect is due to the laser beam partially reflecting off the edge of an object giving a "false point" that appears by itself out in space. The edge effect phenomenon worsens with increasing spot size and is often more pronounced with phase-based scanners, which rely on integrating consecutive point samplings.

d) Close range – Make sure the scanner is calibrated for close range and validate the scan data at the close proximity by checking the length of a standard scale bar and by taking measurements from the scan.

e) Surfaces – Textured surfaces (less reflective) produce better results than smooth surfaces. Extremely dull surfaces of a dark color present problems.

f) Reflective objects – Need to use white powder to make the objects non-reflective (opaque).

g) Intensities – Varying intensities of point cloud are due to variations in reflectivity as a result of color variations.

h) Personnel obstructing objects being scanned – Keep the personnel out of the scan envelope.

- The point clouds from the laser scanner are very large and data intensive. They are not easily managed by CAD programs. Additionally, the proprietary nature of the post processing software suggests limited availability and dedicated training in all cases.
- Post processing the scan data set into 3D CAD models is manual and labor intensive at the present time.
- In photogrammetry (FotoG), the procedure of randomly placing the NIST traceable scale cross bar (1 meter) in the compartment resulted in a coordinate system that is not associated in any way with the ship's coordinate system. This in turn made it difficult for the CAD designers to recreate the individual components within the compartment. This suggests that a procedure for alignment of the NIST traceable scale cross bar (1 meter) with the ship's coordinate system is needed. In addition to the placement of the NIST traceable scale cross bar (1 meter), placement of the coded automatically recognizable targets for photogrammetry should focus on known datum points (ex: directly on the grid tags of the vessel).

- Photogrammetry (FotoG), like total stations, if used in tandem with the laser scanner has the potential to assist in accurately linking multiple scans. Doing so will avoid the use of the troublesome "best fit" routines in the laser scan data post processing software.
- Digital photogrammetry (FotoG process) needs proper lighting to improve picture quality and a steady hand and skill in taking sequential photos.
- Creating 3D CAD models from the FotoG process requires an experienced 3D AutoCAD designer and is labor intensive.

8. Benefits

8.1 Realized Benefits

The research team was comprised of LIDAR hardware and software developers, service providers, and a shipyard contingent of research engineers/designers and survey technicians. The service providers, research engineers, designers, and survey technicians were continuously challenging the data collection and processing methods of the developers in an effort to guide the development and efficiency of the LIDAR based products toward shipyard use. The developers and vendors were performing essentially the same function on each other but at a different level.

The ship check process developed to capture the as-built ship data in digital format and to import the as-built digital data collected into a CAD environment will benefit the shipbuilding industry in several ways:

- ♦ Reduction or elimination of costly "return visits" to the site for measurements that are normally missed using traditional ship check methods.
- ♦ More accurate, complete as-built data for retrofit design projects, which translates into better retrofit designs. These translate, in turn, into less construction rework due to interference and fit-up problems and ability to factory-fabricate instead of having to field-fabricate. These translate into cost savings and cost avoidance.
- ♦ Experience gained from this effort with retrofit design projects can be leveraged to be used by new construction activities to obtain measurements of as-built conditions with more cost efficient and accurate methods.

Ship check data capture using the available technologies provides cost/time savings compared to traditional ship checks. Performance improvement metrics were developed for this project using the format in Table 1. This is also provided in Section 5.0 of the Statement of Work (Attachment 1 of Technical Investment Agreement (TIA 2006-371) for this project). Table 2 provides the cost/time savings (developed using the format in Table 1) using the data capture technology compared with the traditional ship check method.

The data analyzed and processed from the 3Dguru, Faro LS 880, and Z+F Imager 5003 laser scanners from the two ship checks is accurate within the desired tolerance of +/-3/16" on the as-built measurements of components.

The ship check using the two technologies (laser scanning and FotoG process (photogrammetry)) is quick and needs the least number of personnel (two to three). The data captured is found to be complete and accurate. The point clouds collected can be used in several ways (modeling, validating design to as-built, archiving of the data for future use). The various software applications evaluated are useful to process the point clouds and take measurements in the field. Also, the ship check team can verify that they have collected the complete data required on-site using the software applications like Cyclone and LFM 3D modeling software. This eliminates the need to return to the site for missed data from the first visit.

This project has highlighted the need in the shipbuilding industry to have point cloud processing software that provides more automation to the process for merging multiple scans and creating 3D CAD models. Currently, most of the software application developers for point cloud processing appear to be resisting the need to create a comprehensive capability for the generation of detailed CAD models from the point cloud data.

8.2 Metrics

Performance improvement metrics were developed for this project using the format in Table 1 and are shown in Table 2. Performance improvement metrics were developed and tracked to compare the "as-is" practice to that which is anticipated as project results are implemented. This project reports the cost/time savings metrics associated with post processing the ship check data into 3D CAD models compared to creating CAD models using the traditional ship check method with tape measures.

Metric	"As-Is" Baseline	Project Goal	Tracking & Reporting Plan
Time and cost to collect measurements onboard a ship and create 3D CAD models from this information.	*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.*	*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.*	*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.*

Table 1: Performance Improvement Metrics

Figure 10 shows the design model of the Candies IMR valve station in AutoCAD, which was used to develop the performance improvement metrics for this project. The project team estimated time and cost associated with the use of traditional ship check methods (manual sketches, tape measurements, etc.) to create a 3D CAD model for the valve station shown in Figure 10 and compared that to time and cost associated with the ship check of the valve station using the data capture technology (laser scanning and survey) and data processing methods to create the 3D CAD model as shown in Figure 11. Figure 12 shows the laser scan (point cloud) of the valve station in the engine room of the Candies IMR vessel.

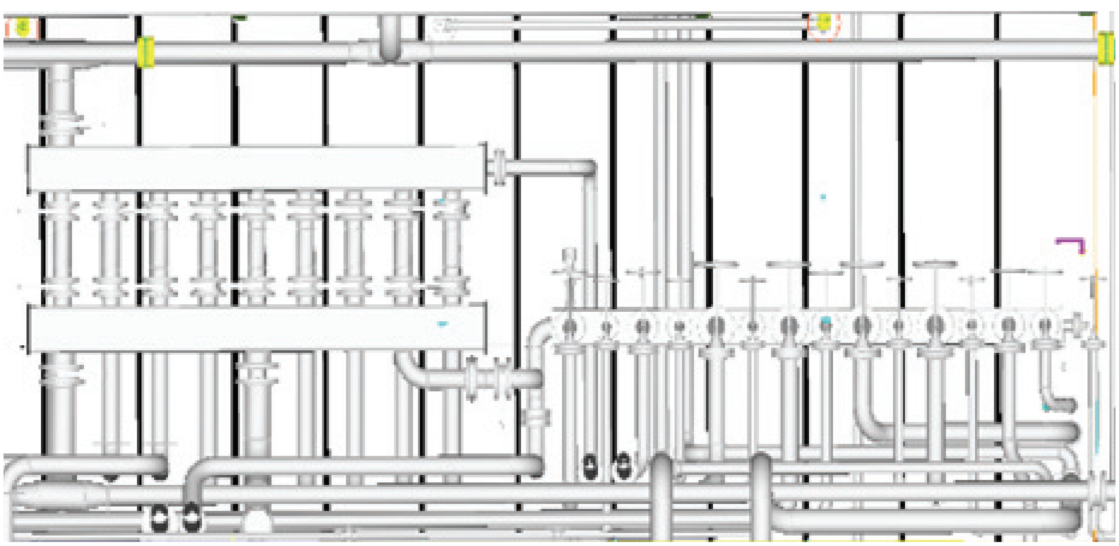

Figure 10:
Candies IMR Engine Room Valve Station Design Model in AutoCAD

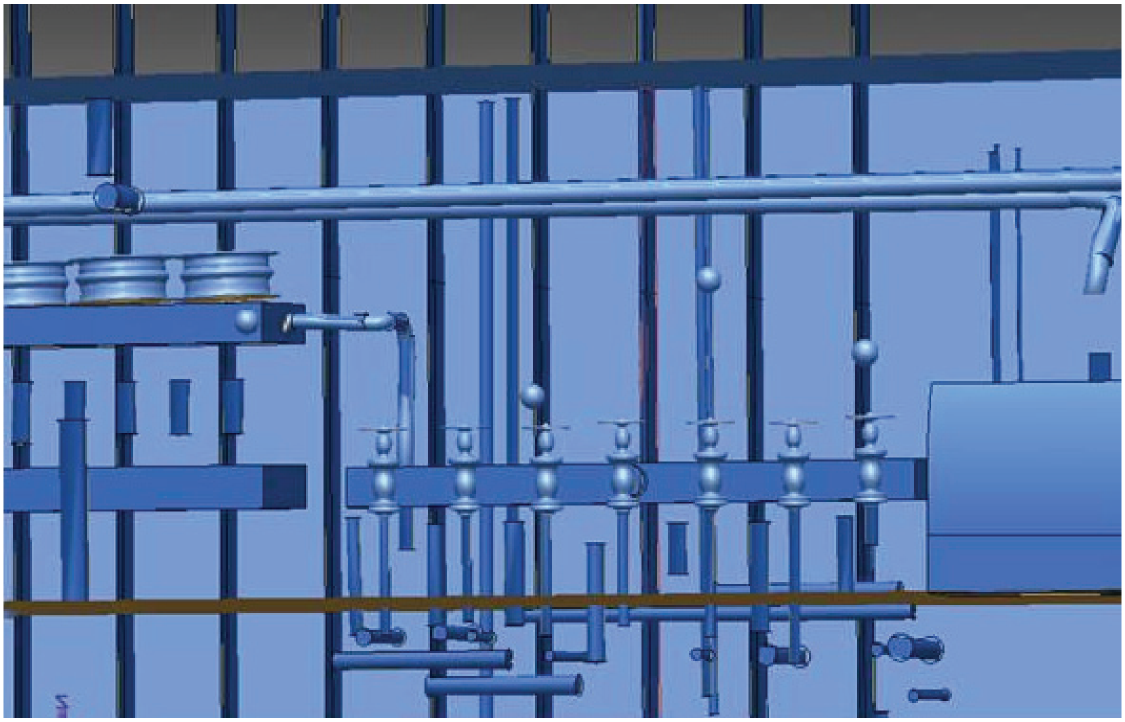

Figure 11:
Candies IMR Engine Room Valve Station As-built 3D Model in RapidForm from Scan Data using RapidForm/AutoCAD

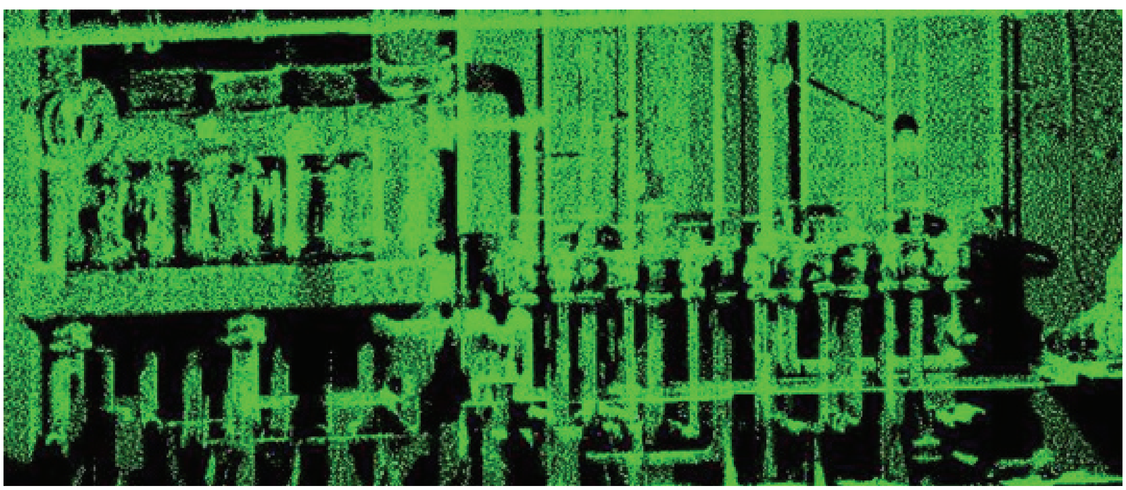

Figure 12:
Candies IMR Engine Room Valve Station As-scanned Data (Point Cloud)

The scan data of the valve station of the Candies IMR vessel engine room from Bender ship check was post processed into 3D as-built model as shown in Figure 11, with the available COTS laser scanning technology hardware and software tools. The time needed for this effort and the cost associated with the ship check data capture were recorded and shown in Table 2. Table 2 shows estimated cost savings of 37% and time savings of 39% for typical ship check post processing efforts of the valve station from the ship check data capture compared to the traditional ship check using tape measures and manual sketches. The cost and time savings shown in Table 2 are above the project goal savings shown in Table 1.

	Traditional Ship Check/Creating As-built 3D CAD Model (Estimate)					Ship Check with Laser Scanning/Post Processing of As-built 3D CAD Model (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 Lodging $125 Car Rental $45 Per Diem $43				$1,200 $750 $90 $387	$2,427				$800 $500 $90 $258	$1,648	$779	
Total Cost/Time		118	$5,900	$2,427	$8,327		72	$3,600	$1,648	$5,248	$3,079	46

Table 2:
Ship Check/Post Processing of Candies IMR Valve Station - 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%

The cost savings do not include the potential elimination of additional ship checks that may be needed to obtain missed measurements when using traditional ship check methods. For the ship check with laser scanning, the data needed will be archived in scans which can be obtained anytime as needed. Post processing efforts with the data capture technologies will provide quality design models and thus produce cost savings in the form of cost avoidance, reduction of scrap, and reduction in labor (direct and indirect) as mentioned below.

The evaluations have shown that the post processing software applications are capable of merging the multiple laser scans and creating CAD models of the ship as-built conditions. The merged point cloud of multiple scans can be used for obtaining measurements. The creation of the 3D CAD model from the point cloud is manual and presently not cost effective, but importing standard library parts (pipes, panels, etc.), overlaying onto the point cloud and creating the 3D CAD model may be. The post processing software applications at present are capable of taking measurements and performing clash detection with the design space to as-built space.

Ship check data capture using the laser scanning technology also provides time and cost savings in the following areas:

- **Labor (Direct & Indirect)**

Data collection with ship check data capture will reduce the ship check time and the number of personnel needed by approximately half compared to the traditional ship check using tape measurements and man made sketches.

- **Rework**

Data collected will be complete and accurate and thus will minimize rework during construction.

- **Scrap**

Since rework will be minimized due to reduced hits of components or foundations because of the design being more accurate with the data collected using this technology, the material scrap is minimized. This provides material cost savings.

- **Schedule**

Less field time is needed with the ship check data capture, and construction schedules will be shorter due to fewer delays associated with rework and re-design.

- **Cost Avoidance**

Use of this technology will minimize rework at construction phase since the as-built data collected is accurate for refit design work and thus reduces or eliminates rework during installation. This in effect reduces construction costs.

Bender Shipbuilding personnel used the ship check scan data of the spaces (stern, Z-Drive, moon pool, moon pool door, engine room, bow, and bow thruster recess) to overlay onto the design model in their CAD system (ShipConstructor) and found most of the as-built condition matched to the design data except for the moon pool door. It was found that two stiffeners of the moon pool door were installed in a wrong location. Since this was investigated during the construction stage, the problem was rectified immediately by installing the stiffeners at the design locations. Bender Shipbuilding finds this technology useful during new construction to validate as-built conditions to design.

9. Issues

None

10. Conclusions

The following are the conclusions of the ship check data capture project:

- The technology (hardware/software) is mature enough to support the ship check process. Laser scanners provide a cost effective method to collect as-built data during ship checks as compared to traditional methods. Laser scanning technology will collect as-built data in a manner which will provide time and cost savings to the shipbuilding industry. The next steps of implementation of ship checks with data capture technology are up to the shipyards.
- The ship check data capture follow-on project resolved the remaining issues from the FY05 ship check project. The results are included in this report and are summarized as follows:
    - The follow-on ship check project confirmed the necessity of conducting a survey during the ship checks to merge the scans accurately. A survey with a total station or a photogrammetry camera during the ship check is critical to align the scans quickly to the global coordinates of the ship and also to create an accurate as-built configuration model of the space.
    - The scan data measurements from the scanner being used to collect the data during the ship check need to be validated on-site during the first use of a scanner with standard scale bars or a survey with control points to obtain accurate ship check data.
    - Field verification of completeness of data collection before leaving the ship check site with the use of a software application like Cyclone is a must to eliminate return visits to the ship. The point clouds of multiple scans can be merged on-site using Cyclone 5.5 from Leica Geosystems HDS, Inc. and the similar LFM control software from Z+F Inc., and they can also be used for obtaining measurements on-site. Although Cyclone was the only software evaluated during this project that was shown to be useful in verifying complete coverage of data collection on-site, CSA, Inc. has used the LFM control software and has stated that it also has this capability.
    - The data analyzed and processed from the 3Dguru, Faro LS 880, and Z+F Imager 5003 (Leica HDS4500 is identical) laser scanners from the ship checks of this project is accurate within the desired tolerance of +/-3/16" on the as-built measurements of components. This was an open question under the FY05 Ship Check Data Capture Project.
- The benefits of conducting ship checks using the data capture technology are: 1) Creation of as-built 3D models and validation of as-built models to design models; 2) Reduction of costly design changes and improved design capability; 3) Reduced construction rework; 4) Accurate and less costly factory-fabricate in lieu of field-fabricate; 5) Reduced ship check costs: fewer days, fewer personnel; 6) Elimination of return visits to the site to obtain measurements of missed data which can happen with traditional ship check methods; 7) Obtaining measurements which are difficult or unsafe for human reach; 8) Scan data (point clouds and associated models) that is readily transferred between computer systems using standard methods such as IGES, STEP, STL, and DXF.
- The demonstrated uses of scan data from the ship checks are: 1) Creating 3D as-built models of the entire space (not cost effective at present), 2) Taking measurements (requires experience), 3) Validating 3D CAD models to as-built data by overlaying as-design or new design CAD model onto point cloud to check placement of components and interferences (cost effective), 4) Creating 3D as-built arrangements by placing library CAD model parts on location using the scan data (cost effective), and 5) Creating surface models for visualization and analysis (cost effective).
- The photogrammetry (FotoG) process may be able to be used to complement the laser scanning technology process. The generation of a usable CAD model from FotoG is a manual and difficult process. The combination of these two technologies may speed up the modeling process and also validate the data collection from each of the two processes. A complete evaluation on the synergy between these two technologies is beyond the scope of this project. It is, however, highly recommended that such an evaluation be accomplished by shipyards and NSRP in the future.

- A significant vendor network exists to support ship checks with data capture and post processing efforts. Shipyards should consider using vendor services for ship checks to assist them in their initial use of this technology.
- Traditional ship checks are still needed for some measurements which cannot be obtained by the data capture technology.
- It is clear at this point in the research that, while all phase-based scanners used for the ship check project offer unique features individually, all of them are capable of meeting the shipbuilding community's needs. It has been determined from the SSGN 729 ship check that these scanners can be used on a surface ship as well as in the tight confines of a submarine. With adequate training, a new user can quickly become proficient in their use. These Light Distance and Ranging (LIDAR) phase-based scanners, the tools, and their operational software are relatively easy to use and are user friendly.
- The Minolta Vivid 9i Digitizer used under the FY05 project is a short range, high accuracy, fixed head, small field of view scanner that requires a large number of scans to keep pace with the phase-based scanners. It is not suited for the relatively large ship check projects onboard ships. This digitizer can be used during ship checks which require minimum areas to be ship checked.
- The point cloud from the laser scans are very large and data intensive; they are not easily managed by the CAD programs. Some of the processing software applications evaluated are not capable of importing scans in full resolution due to PC memory constraints. This affects the accuracy of the as-built models created. This problem needs to be resolved by software vendors developing methods to obtain greater accuracy from larger datasets.
  - The size of the scan data sets being processed in the PolyWorks software necessitates the need to have an adequate amount of memory and processing power in the work computer. The fraction of raw point cloud data imported from the original scans in PolyWorks will affect the quality of the data measurements achieved. It is recommended to break the scans into small segments and import the segmented scans in PolyWorks at 100% strength and then clean up the data. This method will provide more accurate space data than importing the data at a fraction and also at a lower resolution in PolyWorks and then cleaning the data.
- The creation of 3D CAD models from the point cloud is labor intensive and not cost effective at this time. This needs to be addressed by the post processing software vendors so that they include such functionalities in future releases of their software.
  - Importing standard library parts (pipes, panels, etc.), overlaying the parts onto the point cloud, and creating the 3D CAD model could be a cost effective alternative method of verifying component locations.
  - Most of the software developers seem to be resisting the need to create a comprehensive capability for the generation of detailed CAD models from the point cloud data. Their position is: "the point cloud has all of the required data found in the 'as-built' CAD model; to actually create the 'as-built' CAD model is a redundant effort". They suggest that all measurements, comparison between "as-designed" and "as-built", and reverse engineering can be accomplished using the "as-designed" CAD model and the point cloud. This rather short-sighted point of view may well be the case but it does not consider the usability of the software, the user's capabilities, or all entities that may require access to the data.
  - The scan data can be post processed into 3D as-built solid models manually with the use of several software applications such as PanoMap, Cyclone, Spatial Analyzer, RapidForm, and Mechanical Desktop.
  - Initial evaluation shows that these post processing software applications are capable of merging the multiple laser scans and creating CAD models of ship check as-built conditions. Some of the software applications, like PolyWorks and FotoG in AutoCAD, are not user friendly and require extensive training.

- The laser scanning technology provides time and cost savings to the shipbuilding industry during ship checks for overhaul and refit/repair work, for reverse engineering efforts, and for validation of as-built to the design CAD model during overhaul & repair, ship alterations, new construction, and facilities redesign.
- Performance improvement metrics were developed for this project. An estimated cost savings of 37% and time savings of 39% 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%. More cost savings will be realized with the use of the laser scanning technology for ship checks from cost avoidance and minimized rework.
- Phases I and II of the NSRP ASE ship check project are now complete. Annex–I provides the refined ship check process developed under this project.
- Annex–J provides a "Consumer Reports" like evaluation with pros and cons of the hardware and software of the two data capture technologies (laser scanning and close range photogrammetry) evaluated under Phases I and II of the ship check project.