DIMENSIONAL & ACCURACY CONTROL AUTOMATION IN SHIPBUILDING FABRICATION: AN INTEGRATION OF ADVANCED IMAGE INTERPRETATION, ANALYSIS, AND VISUALIZATION TECHNIQUES

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ABSTRACT:

Dimensional and accuracy control automation is becoming a reality for the shipbuilding processes within the General Dynamics Marine Division at the Bath Iron Works Corporation. Digital close-range photogrammetry data acquisition and processing techniques are being combined with customized analysis and visualization development to provide the shop floor with the ability to automatically measure and analyze 3D plate burning quality, while at the same time assess the impact of as-burned plate quality to down stream stages of construction. Unique to this project and critical to successful application is the development, evaluation, and integration of 3D point measurements through edge detection with consumer off the shelf type components This approach has lowered costs and facilitated highly accurate and reliable measurements, while providing user friendly operability and enabling future technology growth. This paper presents the project approach in theory and documents the actual experiences from production implementation. In conclusion this paper will also provide a summary that outlines future plans, calling for this strategy to be implemented throughout the remaining construction processes of panel fabrication, unit assembly, and ship completion.

1. INTRODUCTION

1.1 Background

The Shipbuilding Industry provides a dynamic environment for a diverse range of measurement applications. Traditionally known more for the use of plumb bobs, steel tapes and transits, this industry has slowly opened its doors for the use of more current three dimensional type equipment (theodolites, laser trackers, digital photogrammetry, etc) for single application, off line, production support type measurements. At the Bath Iron Works (BIW) shipyard (located in Bath, Maine USA) another advancement in measurement technology is occurring through the development and integration of a digital photogrammetry based, online Dimensional and Accuracy Control Automation (DACA) system to monitor the as built dimensional quality of steel plates/components as processed through key fabrication, assembly, and ship completion stages of construction.

1.2 Emergence of DACA in Shipbuilding

Although the initial strategy and design of DACA was first submitted and approved by the US Navy Manufacturing Technology Program in 1996, the emergence of DACA in shipbuilding first took shape when a BIW Continuous Process Improvement initiative reported that digital (as opposed to analogue) photogrammetric techniques were mature enough to warrant R&D investment (Johnson, 1993). This report was verified in the field through a cooperation with the Swiss Federal Institute of Technology in Zurich, Switzerland when the BIW/ETH team proved that measurement accuracies using a KODAK DSC200mi digital camera, combined with ETH processing software and a computer workstation, were well within shop floor requirements (Maas and Kersten, 1994). Experiences gained from the implementation of a digital close-range photogrammetric system as combined with CAD data and Statistical Process Control software could yield an integrated approach to satisfying short term production needs for immediate measurement support as well as securing long term goals regarding quality control (Johnson, 1996).

1.3 Direct Benefits of DACA

The significant benefits derived from DACA for selected processes are of an economic and social nature. Due to the online integration approach, three dimensional data can be measured, analyzed and reported much more efficiently than manually taped two dimensional linear distances, accuracy control check sheets, and statistical process control charting could provide. This cost effectiveness is complimented by increased data, higher accuracy's, enhanced visualization of results and increased sharing of reports. Simply stated, this provides an increasingly reliable picture of overall product and process quality to all appropriate levels of the company, within minutes of the measurement being performed. The targeted impact being that quality control type assessments are faster and better while enabling all essential personnel to approach their jobs in a more informed manner.

2. APPROACH

2.1 DACA Methodology

The combination of CAD information with automated, image based metrology through 3D edge detection techniques and customized analysis and visualization methods represents a significant leap forward in shipbuilding production process control and automation. In order to maintain an organized approach towards DACA across key stages in the shipbuilding process a Structural Measurement and Analysis System (SMAS) interface was developed (Figure 1).

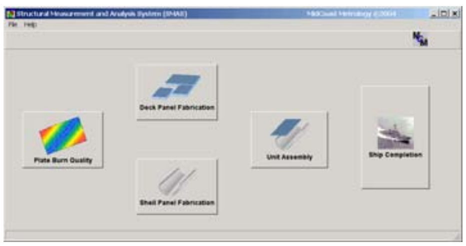

Figure 1. SMAS Interface

This interface not only portrays corporate intent and strategy but also provides the user with direct connectivity to the appropriate application for structural measurements, measurement analysis, or process control activities. For the shop floor mechanic and accuracy control technician this means being provided with the ability to quickly and accurately view a part to design (perhaps part to part) comparison and statistical information related to product quality, process control and capability goals for each plate burned. Attributes of interest include lengths, widths, squareness, straightness, and flatness. In parallel with the burning machine development, the accuracy control technician will also get the added functionality to further investigate individual plate quality as well as view the as-burned quality of multiple plate configurations as they would be fabricated into deck panels. By approaching DACA in this manner; adjacent construction process quality is directly connected to the inputs/outputs and daily activities of each other. Equally important is the fact that process improvements regarding quality, costs and schedule are realistic, measurable, and communicable throughout all levels of the organization (if desired).

2.2 Hardware Configuration

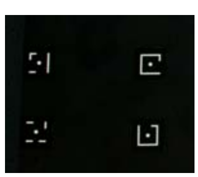

Image 1.
Canon 1Ds digital SLR camera

Image 2.
VMS coded targets

A critical specification for all equipment was to maximize the use of consumer off the shelf components in a manner that facilitates technology growth, application development, user friendliness. Accordingly, the camera chosen was a Canon 1DS, an 11 mega pixel, digital camera (CMOS sensor). The workstation for developmental processing, analysis, and visualization was a Dell Precision 650, with dual 3.06GHz Intel Xenon processors, 1 GB of RAM, and 4 by 146 GB SCSI drives. Part movement (and image acquisition rate) was determined by using 3 proximity switches configured in conjunction with a PLC based electrical switchboard. Cabling between the camera, workstation was via IEEE fire wire whilst all other networking and/or electrical connectivity was accomplished using standard cabling.

2.3 Determining Plate Geometry

The image processing for the DACA Plate Burn Quality system is performed using VMS. VMS is an acronym for Vision Measurement System and comprises a main program and a number of dynamically linked libraries written in the Visual C++ language. VMS commenced as a research tool in the mid 1990s (Robson and Shortis, 1998), but is now a commercial product in use for industrial metrology, surface characterisation and tracking (Shortis et al, 2002) and determining the biomass of fish for aquaculture (Harvey et al, 2003).

The primary function of VMS is the photogrammetric network adjustment of 2D measurements to target images, so that the most probable 3D object space coordinates of the targets can be determined. VMS may also be used to simultaneously determine the calibration of the cameras within the network either as a primary task or as a secondary benefit. Coded targets (Shortis et al, 2003) can be used in conjunction with VMS to improve the efficiency of the measurement process.

The photogrammetric adjustment within VMS uses the principle of co linearity and an iterative least squares estimation process to compute resections/intersections or to adjust photogrammetric networks. Initial estimations for camera orientation are computed automatically using the Zheng-Wang closed form resection, based on automatic detection of coded targets. Resection and intersection computations use an L1-norm robust estimation to reliably remove outliers in the target image measurements.

Networks may be processed with or without self calibration, with a choice of three different additional parameter sets, and can be processed as free networks (internally constrained by all targets) or externally constrained by control targets with known coordinates and optionally including survey measurements such as inter-target distances.

2.4 As-Burned Part to CAD Analysis

The as-burned to CAD analysis for the DACA Plate Burn Quality system is performed using PolyWorks/Inspector. This software provides exceptional power and functionality regarding the preparation and analysis of point cloud data when performing part to part and/or part to CAD comparisons.

Of major importance to the DACA approach are the unique automation capabilities that are available to support the entire analysis process. From importing and aligning data to customized geometric dimensioning and tolerances (GD&T) reports the macro recorder and scripting language enable direct integration to the original SMAS screens and streamlines and standardizes the initial Quality Inspection process for measurements performed on the plates directly from within the burning process at the shop floor.

Of equal importance is the ability to further the inspection process manually for a more detailed dimensional analysis. This ensures that the diverse range of part shapes as well as production requirements can be sampled online or offline.

Another important aspect of PolyWorks/Inspector is the ability to provide 3D measurement information for direct integration with other software(s) like Statistical Process Control (SPC) and Production Simulation. DACA methodology stresses not only part quality but also in assessing and sharing the effect that part quality has on Production through put as a whole.

3. APPLICATION: PLATE BURNING QUALITY

3.1 Description

The Plate Burn process was identified as the working envelope of the CM150 Burning Machine (Image 1) located within the Hardings facility in Bath, Maine. The throughput for the burning process involves raw steel plating being placed on large tables. These tables are moved from the loading position to underneath the burning machine so that a gantry type plasma burning torch on rails can travel over the table to perform underwater cutting of the raw large steel plating into smaller ship parts or shapes. Once the steel has been cut the ship components are directed towards the next stage of construction and the scrap is placed into collection bins for removal.

Image 3. CM150 burning machine area

The production requirements for DACA integration were simple but demanding. Here the tasking was identified as developing a one button type system for the automated measurement and analysis of large flat steel panels to an (XYZ) accuracy of plus/minus 2mm without interrupting production. Absolutely no targets could be placed on the object to be measured (ship components burned from the raw plating). The system had to be safe, user friendly, cost effective, reliable, maintainable, upgradeable and compliment existing production through put levels. An important note here is that the shop floor environment is very dirty, noisy and busy, with much vibration due the handling of steel in a number of ways and directions.

3.2 DACA Integration

All hardware and software components were integrated into a graphical user interface (Figure 2) that governs all data acquisition, processing, reporting, and archiving activities. The system is live at all times, being regulated by proximity switches that monitor the location and/or movement of the tables that the plates are burned on. As the tables are rotated through the burning process the digital camera mounted at the end of the burn station and directly over the center of the table path acquires imagery at a predetermined rate.

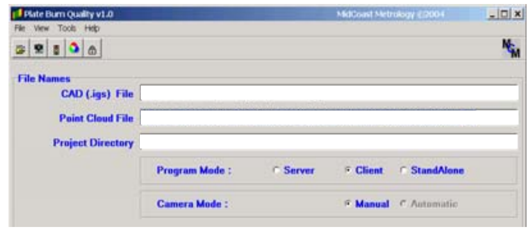

Figure 2. Plate Burn Quality Interface

The process is worked from left to right within the user interface and commences when either the burning machine operator or Accuracy Control Technician first selects the proper part drawing (Iges format) from a pick list. Next the camera button is selected to move the images from the camera to the appropriate workstation while also setting up the proper file structures for processing. Then the run button is selected and VMS processes the imagery so that PolyWorks can then analyze the edge measurements. The final results are available for local shop floor or corporate visibility by selecting the reports button. The final button unlocks administrator area in which initial settings for all hardware(s) and software(s) are set up and maintained.

3.2.1 Acquisition: Image acquisition is acquired from the Canon 1Ds at the approximate rate of one image for every three feet of table travel in high resolution JPG format. Great care was afforded to proper camera settings to facilitate the best edge detection possible. For this application trade offs in image quality with respect to edge sharpness, retro bleeding, and environmental influences occurred at or near setting of ISO200, F9.0, with a shutter speed of 160sec. Image storage can be at the camera itself (using a 2Gigabyte memory card, which currently allows for approximately one weeks worth of unattended data acquisition) or via the BIW intranet/LAN for a potentially unlimited amount of space and/or time period.

3.2.2 Measurement: The requirement not to use any targets on the plates themselves dictated the careful illumination of the plates and their cut-outs so that edge detection would be able to deliver consistent measurements. The network geometry was governed by the use of a single camera with the table travelling below it delivering geometry not dissimilar to a strip of aerial mapping photography.

Images 4, 5, & 6. Burned plate 'image strip'

Following stringent testing with a variety of edge detectors (Gaussian based wavelet, Canny and Sobel), the Sobel detector became the method of choice. Whilst this may be surprising due to its simplicity and limitations when compared with the other methods, the quality of the edge images obtained was such that the Sobel method could provide appropriate edge information at the cut outs in significantly less time. Details of the measurement abilities of these detectors when applied to this project are given in section 3.2.4.

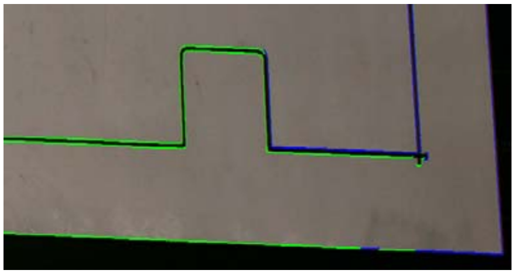

Image 7. Plate burning edge extraction

Coded target scanning, resecting, and running an edge detection and edge point linking procedure produced a set of registered edge images. A correspondence solution was then attained using epipolar geometry derived from each detected point on each edge into its neighbouring images. Due to the close proximity of detected edges either side of cutting lines and the weakness in geometry of the single strip of images, it was deemed appropriate to introduce a depth constraint which specified a maximum and minimum depth for the plate being measured.

The highly constrained geometry of the solution is necessary as a substitute for the robust analysis techniques associated with convergent, multi-image networks. For example, each edge point generally appears on only three non-convergent images, so techniques such as a balanced L1 norm analysis of the intersections cannot be applied to confidently eliminate incorrect edge correspondences.

Following correct edge correspondence, intersection was used to compute the location of each edge point. These data along with their associated statistical properties were exported into PolyWorks for comparison between as built and design.

3.2.3 Analysis & Reporting: Point cloud analysis is performed using PolyWorks/Inspector. The scripting language enables the creation of a customized macro that with proper file structure and preparation can automatically import and align the CAD drawing as well as the as-burned point cloud as well as conduct part to CAD comparisons. The results are then provided (automatically) in graphical (Image 8) and textual files in the form of dimensions/tolerances and/or deviations.

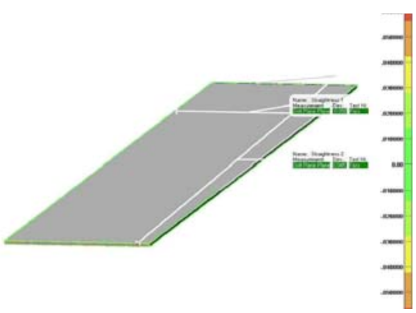

Image 8. Sample output report for Plate Burn Quality

3.2.4 Results: The results provided (Tables 1&2) are based on shop floor measurements over the project's setup and initial integration period. Data capture was performed over the duration of the project and is extensive. Emphasis for this paper is to provide result summaries that pertain to system preparation and implementation being fit for use; the accompanying presentation will provide more details.

Camera Calibration Summary		
Description	Relative Accuracy	
20mm Lens		1:98,000
24mm Lens		1:210,000
Process Through Put (minutes)		
Description	Small Plates	Large Plates
Acquisition	3	3
Processing	3	3 to 20
Analysis & Reporting	0.02	0.020
Image Acquisition Reliability		
Description	Acceptable	Failure
Initial Preparation	14800	58
Integration	4800	0

Table 1. Summary of results during project start up.

When undertaking a project such as this proper hardware and software selection is essential. Since VMS (edge detection processing, project simulation, and multi camera enabled) and PolyWorks (point cloud analysis) was the foundation of choice by BIW the next step was to select the proper camera and determine the proper site and equipment configurations. Based on previous experiences regarding accuracy and reliability in the field the Canon 1Ds Digital SLR was selected as the camera of choice. Project simulations and preliminary testing showed that 20mm to 24mm lenses were optimal for this application's working envelope.

The ensuing calibrate – test, calibrate – test, etc. process was performed repeatedly over a 3 month span by taking the camera in and out of the production environment and conducting measurements on a retro reflective calibration wall at MidCoast Metrology. Calibrated scale bars, internally constrained, and externally constrained bundle adjustment were used throughout. The initial edge detection measurements were conducted using a calibrated orientation cross located at the center of the burned plates. The results (Table 1) confirmed that the 24mm lens was indeed much more accurate that the 20mm lens although there was a slight trade off in terms of the size of the image area acquired. This was overcome by manually raising the camera height by approximately 1foot and adjusting the rotation of the camera.

Working in parallel with the camera configuration was the integration of the proximity switches to acquire the digital images automatically. This was accomplished by setting up 3 switches; two to activate the system by monitoring table movement and another to count activate the camera by counting the teeth of the chain drive that moves the tables. Although the physical setup was minimal (3 days), the testing was performed over a two month period in which fine tuning optimized the all aspects of the image capture process. Simply enough the limiting factor was identified as being the refresh rate of the flash source. Although the images were being taken at a 100% success rate a worse case scenario could provide every 10th image as being too dark for measurement. Once a correction was made to slow down the proximity switch count rate the image acquisition process has run without error.

Control Accuracy (inches)			
Description	X	Y	Z
Baseline 1 (rms)	0.007	0.007	0.012
Baseline 2 (rms)	0.008	0.007	0.014
Deviations BL1 to BL2	0.001	0.001	0.002
Edge Measurement Accuracy (inches)			
Description	X	Y	Z
Integration + 0 Days	0.032	0.031	0.057
Integration + 30 Days	0.038	0.037	0.068
Best results	0.021	0.021	0.033
*Worst results (non fail)	0.195	0.193	0.320

Table 2. Summary of results during initial implementation.

Once the system was ready for implementation control points were installed at the perimeter of one of the burning tables. Measurements were performed to determine the X, Y, Z locations for each point using a KodakDCS660M and the aforementioned calibrated scale bars. Table 2 shows that the original point location was determined accurately with repeatability. Since interruptions to production must be kept to a minimum increased accuracy/repeatability measurements were not allowed at the time of initial implementation but rather is scheduled for routine check up every 3rd month of implementation or as needed by monitoring any accuracy degradation incurred from the system over time.

With the perimeter control in place measurements were then obtained by sampling the burned plates on a daily basis. This was a very crucial aspect of the project in that for the first time all areas of development were beginning to come together as opposed to being worked in parallel. Areas of significance included measurement accuracy's being consistently within the required plus/minus 2mm for the plates sampled (Table2) which were consistently within the project requirements of plus/minus 2mm. The exception to this is if the targets are not maintained a noticeable degradation in accuracy and ultimately measurement (resection failure) was noticed. The degree of automation realized is best portrayed by Figure 2 where settings for client/server, stand alone, manual, and/or automated measurements can be established. Finally the customization of the user interface to facilitate a wide range of implementation scenarios (degree of automation included) was significant. Although the original project specification was for a closed loop shop floor, single button type system the final product implemented encompassed considerably more open architecture enabling networked data capture and analysis.

4. CONCLUSIONS

4.1 Production Impact

As with most quality/production improvement initiatives, the strengths and weaknesses of the DACA project at BIW relies on the use of the data obtained. Constancy of purpose and dedication at all levels of the organization must prevail in order for the system and its associated information to succeed. This new method of automatically obtaining data and visualizing results (textually as well as graphically) must be accepted and optimized without abuse and/or neglect.

Quality		
Description	**Traditional**	**DACA**
Measurement	Linear Distance	3D Coordinate
Accuracy XY	0.060"	0.030"
Accuracy Z	None	0.060"
# of Data Points	5 Distances	1000+
Reliability	Not monitored	RMS monitored
Cost (hours)		
Description	**Traditional**	**DACA**
Measure	30	30
Analyze	15	0.02
Report	15	0.02
Schedule (minutes)		
Description	**Traditional**	**DACA**
Production Delay	30	0

Table 3. Comparison of traditional measurements to DACA

The comparisons in Table 3 prove that the SMAS system is fit for use and is decidedly better than the traditional approach especially when considering future production (data) requirements). Although the release of proprietary information sensitive to corporate performance is not allowed the following statements can be made:

- ✓ Measurement quality has been improved through improved accuracy, more reliable data, more complete data, and the data now of three dimensional coordinates with error statistics available instead of simple two dimensional linear distances.
- ✓ Overall costs are reduced in that the time spent to operate and maintain the SMAS system and achieve significantly better results is less that it would be to measure, compare, and plot plate burn deviations manually (in 2D).
- ✓ The impact to schedule during development has been nil while the integration could see an improvement of up to 30 minutes per table since the plates are to be measured from automated image acquisition (i.e. no one has to physically climb up on the plate and thus delay the table from moving to the next station)

4.2 Social Impact

It is important to note that this is a prototype system and as such there much is to be learned over time regarding people, equipment, methods, and the application environment. With proper maintenance shop floor integration has been proven to be scientifically stable. Social concerns will remain a vital factor through integration. At the heart of this concern is the delicate balance that this type of development brings regarding; whether this type of tool is to be used to replace people or is this a tool to help workers improve their performance and/or capabilities. Only time will tell but considering the track record at BIW for DCRP integration it is fully expected that this initiative will result in the workers being enabled to do their jobs better as well as obtain a much better three dimensional understanding of their ship building processes.

4.3 Strengths & Weaknesses

Generally speaking DACA integration, current and future, looks very optimistic. The System components selected have good track records thus far. Still it is very hard to predict long term equipment performance due to the prototype nature of the DACA system and the relatively new introduction of the Canon 1Ds camera into online photogrammetry measurements.

The potential strengths of DACA at BIW involve improved data quality/quantity and measurement automation. By acquiring better and more comprehensive data and enabling the shop floor operator and accuracy control technician to better understand the quality of goods and services in his/her local areas the benefits derived are limited only by the dedication and imagination of the people involved. Even though there are always constraints (budget, time, access, training etc.) if the system is user friendly and useful, the work force will typically find a way to push the envelope and come up with ways to either make things better through change or simply use things more efficiently as is.

The potential weaknesses of DACA at BIW (other than the social concerns mentioned in section 4.2) are quite specific and involve data use and target maintenance. Target maintenance is easy to overcome with a preventive maintenance plan. In the case of the Plate Burning Quality application the targets will be cleaned every to weeks while the control points and camera calibrations will revalidated every 3 months of use (or as needed from monitoring the resection residuals).

4.4 Future Considerations

The future looks bright for DACA at BIW. Plans are already being made to further its integration within Sub Assembly, Assembly, and Ship Completion stages of construction. The challenges; will however, be significant as the working envelopes will increase dramatically, the parts to be measured will be much more complex, and the environmental conditions will be very different from area to area. On site testing has shown the potential for single as well as multiple camera configurations as well as remote data acquisition and system maintenance.

Although not practical within current funding levels and production requirements the stage is set for one area/office at BIW to be responsible for the dimensional quality and process analysis of multiple stages of construction across the facility. Still the final goal will only be realized when ability to correlate dimensional quality with labor estimates and production schedules is realized. When DACA reaches this point the shipyard will realize an optimum point in terms of production support capabilities as well as the ROI involved.

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6. ACKNOWLEDGEMENTS

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