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3-D Computerized Measuring Systems for Increased Accuracy and Productivity in Shipbuilding and Repair

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ABSTRACT

Conventional measurement and alignment methods for shipbuilding and repair are no longer compatible with today's technology. Measurements made with plumb bobs, taught wires, transits, optical-mechanical theodolites, levels and wooden templates, while adequate in many applications, are labor intensive and leave some redundancy with regard to accuracy.

With the increased popularity and use of the personal computer during the 1980's, several laser, electronic theodolite and photogrammetry based measurement technologies emerged. These methods require highly skilled workers, and although they increased the reliability of measurements, they are costly and again are labor intensive (Horsmon, 1991).

This report describes two computer based measurement systems. Each system requires only a single operator to generate three dimensional coordinates rapidly and accurately. Each system measures in the spherical coordinate system of the instrument. The supporting software programs allow for the transformation of the measured data to the blue print values or object coordinate system. Data can be imported from CAD or lofting software for measuring or locating specific points of interest, or can be exported for comparison of as-built coordinates with design values.

The choice of measurement system employed will depend on the task at hand, accuracy required, environment and budget of the user. Actual shipyard applications stating increased accuracy and/or productivity are cited for each measurement system.

INTRODUCTION

This paper describes two proven approaches to making accurate three-dimensional measurements of large assemblies commonly encountered in a shipyard with a portable computerized system. One system is known as an enhanced single station electronic theodolite and the other as a laser tracker. Each system requires only a single operator. The measurement philosophy is the same for each approach.

Each system measures distance based on properties of a beam of light being sent to a reflective target and then returned to its source. When the light wave is compensated for atmospheric conditions, differences between outbound and return signals resolve the distance to the target with extreme precision. The primary difference between the two system is that the laser tracker distance sensor uses a laser beam projected to a corner cube target. The enhanced single station electronic theodolite distance sensor uses a modulated near-infrared light beam projected to a retro-reflective target.

DEVELOPMENT OF TECHNOLOGY CLOSELY TIED TO SHIPBUILDING

The two technologies presented each have development roots within the shipbuilding industry and have been cultured for over a decade.

In 1982 a working group in the Super Modernization Committee of the shipbuilders Association of Japan, with the participation of Sokkisha Company, Ltd. (an instrument manufacturer), Ishikawajima-Harima Heavy Industries Company, Ltd. and three other shipyards under took the development of a new measurement technique capable of measuring three-dimensional hull blocks of over 10 meters square within an accuracy of several millimeters (Masaaki, 1992).

As a result of this consortium, a distance-angle measuring instrument was introduced in Japan as a commercial product in 1989. The instrument is an enhanced electronic theodolite with a highly accurate near-infrared measurement sensor constructed so that distances are measured co-axially with the telescape line of sight. The instrument was integrated with an electronic notebook capable of recording field data and down loading this data to a personal computer with measurement and analysis software. This integrated system, named MONMOS in Japan, was introduced as a commercial product in 1990. There are over 200 systems being used in Japan today of which more than

50% are being used by shipbuilders.

This technology was introduced to the USA in 1991 by Sokkia Corporation of Overland Park, KS. In 1993, a robust measurement and analysis software product to support the Japanese made instrument was introduced. This MS-Windows• based software was developed jointly with TMA Technologies, Inc. of Bozeman, MT. The resulting industrial measuring system is used in many USA industries including several shipyards.

In 1983, Chesapeake Scientific Instruments, Inc., of Lanham, MD, undertook the development of an interferometer to track an object undergoing random motion to a measurement precision of .008 mm (.0003 in) to .08 mm (.003 in) in three-dimensional space. This work was performed in cooperation with MTS Systems Corporation of Minneapolis, MN, under a Navy contract directed by the NAVSEA Office of Robotics and Autonomous Systems. The resulting product was introduced commercially (Brown, 1986).

In 1988, a measurement services and software development company, Spatial Metrix, Inc. of Westchester, PA, began working on a rigorous MS-DOS• software product in cooperation with the manufacturer of the interferometer. The product was introduced commercially to support the laser tracker. Available as an option was a geometric dimensioning and tolerancing software package to perform inspections and report results. In 1992, the companies merged and the integrated company now located in Kennett Square, PA, is known as Chesapeake Laser, Inc.

Today's product accurately performs static (point to point) measurements and surface contour measurements (scan mode). The system software is an MS-Windows• application program which incorporates dimensioning and tolerancing operations based on ANSI Y14.5. Over forty of the current laser trackers have been delivered to the USA marketplace, including several shipyards, since 1993. The application software has been under continuous development and field testing since 1988.

The above mentioned companies were the pioneers of their respective technologies. Lieca of Unterentfelden, Switzerland, introduced a similar laser tracking system in 1993, and enhanced electronic theodolite measuring system with menu driven MS-DOS based software.

PRINCIPLES OF OPERATION

Each 3-D computerized measuring system discussed consists of an instrument with angle and distance measuring sensors, a system controller (computer), measurement and analysis software, a power source, and targeting. In most cases measurements can be made and recorded with each system by a single operator.

An electronic distance measuring sensor is mounted on a horizontal axis or trunion, so that it sweeps a vertical plane perpendicular to its axis of rotation and centered on a spindle or vertical axis of rotation. Mechanical construction requires that the trunion is precisely perpendicular to the spindle and that the sensor measurements are precisely perpendicular to the trunion. The reference point for making measurements is precisely at the intersection of the trunion and spindle axes. This is referred to as the instrument coordinate system origin. Encoders (precise angle measuring devices), each having an indexing capability, are attached to the trunion and spindle to accurately record the angular rotation of the distance measuring sensor about each axis.

An instrument of this design accurately measures a point of interest (P) in spherical coordinates with Ω = azimuth, Φ = zenith and D = slope distance. The spherical coordinates are then easily converted to cartesian coordinates; X, Y, and Z through the system controller (computer and supporting software) for analysis. The point of interest (target) is referenced to a three-dimensional, orthogonal coordinate system having its origin at the intersection of the trunion and spindle axes of the distance measuring sensor. This is designated as the instrument coordinate system (see Figure 1).

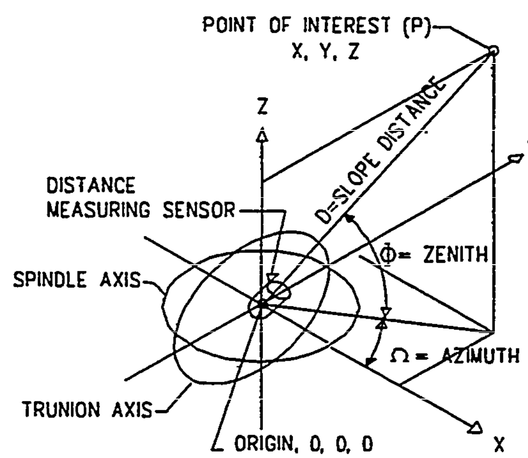

Figure 1 Instrument Coordinate System

For comparison and analysis, points of interest are most often required to be in the design or blueprint coordinate system of the object being measured, or a user defined coordinate system. Additionally, when measuring large objects such as encountered in shipbuilding, all points of interest cannot be measured from a single instrument location. The measuring system controller provides for finding the relationship between the instrument coordinate system and the user defined, or object coordinate system. Also, the relationship between an infinite number of instrument coordinate systems can be defined by the measuring sysstem controller. The process of finding the relationship between coordinate systems and the relationship of points of interest in a coordinate system is known as a transformation or an orientation.

For analysis, the measuring system software allows the user to fit an array of targets to a variety of common geometric shapes using a least squares adjustment. Common shapes may be a line, plane, circle, sphere, cylinder or parabola. These analyses also provide the best-fit values of the parameters that define the shape and a listing of the residues that show how far each point of interest lies from the computed best fit shape. The software will also allow users to analyze the specific geometric relationship between points of interest, objects and shapes as well as the intersection of a point of interest with another shape or object.

The measurement system software allows a user to define the project parameters such as target measurement sequence, atmospheric corrections, axis labels and order, units angular and linear units of measurements and design values for points of interest.

Measurement project information can be printed at any time during or after the execution of a measurement task. Reports can include project parameters, targets, observations, shapes, transformations and comments. Project information can reprinted to a specified database file or to a printer. Data base files can be imported and exported in AutoCAD or ASCII format.

The Enhanced Electronic Theodolite

The single station theodolite is an enhanced electronic theodolite, which incorporates electro-optical modulated light technology based on a near-infrared light emitting diode. The distance from the origin of the sensor coordinate system to the target is measured co-axially with the telescope line of sight. The cross-hairs of the telescope are used to fix the azimuth and zenith position of the sensor. The absolute precision with which distances are measured from the origin of the sensor coordinate system is presently ± (lmm + 2ppm) while relative measurements of targeted points in an array are even more precise as resisual errors in the measurement sensor tend to cancel out. This system uses disposable reflective targets backed by adhesive tape. The targets preprinted with a target pattern for registering the sensor's cross-hairs and feature a micro prism surface to return the distance measurement beam. Tooling targets and offset (hidden point) targets are also available. This targeting method represents a significant advance over the bulky prism targeting used for conventional total station type instruments which normally provide a fine precision of ± 3mm (+ 0.118 in).

The system consists of an enhanced electronic theodolite, industrial measurement software, computer, instrument stand and power source. When a portable notebook computer is used, the entire system can be DC powered, as the instrument can operate on a 6V DC NiCd battery thereby enhancing the portability of the measuring system. A 110V AC power supply is available as an option.

The software, specifically developed for industrial measurement performs all of the functions outlined under principal of operation. The 3-D measuring system features are presented for comparison in Table I.

The Laser Tracker System

The laser tracker is a servo controlled HeNe laser interferometer which is locked onto the target by a servo feedback system The servo motors drive the sensor's azimuth and zenith steering to keep in step with the target motion (if any). The HeNe laser interferometer determines the distance from the origin of the sensor's coordinate system to a resolution of 1/4 wave length of red light (0.1582 microns). The standard target, known as an SMR (spherical mounted retroreflector), is a hollow comer cube optic mounted in a 38 mm (1.5 in) diameter tooling ball. Mechanical centering and interfacing is within .0l mm (0.0005 in). Other target interface configurations are available. An offset is normally introduced between the center of the optic and the point of interest. The system software automatically corrects for this offset when indicated by the operator. Hidden points or surfaces not easily targeted with an SMR can be measured with an offset rod describing a sphere which centerlines at the point of interest or the newly introduce retroprobe based on the concept of a virtual image point.

This system can operate in static (point by point) and dynamic(scan) modes. An SMR can be moved over surfaces and scanned by the laser to easily generate profiles for surfaces with complex contours.

The standard servo system tracks the optical target to a resolution of 2.5 microns at a velocity of 4.0 meters per second. When three or more laser tracking units are used to track a common target, the measurement system is known as a trilateration system which will provide extreme precision in large volume applications.

A typical laser tracker 3-D measuring system requires 110/115 V AC power, and normally is configured to include a laser tracker (instrument), a tooling stand, a remote power supply, computer, software and appropriate targeting. The measurement function may be controlled from the computer, an umbilical cable or with an optional voice recognition system.

The software is an MS-Windows• measurement and inspection software application developed for the tracker technology, and performs all of the functions outlined under principles of operation. Additional features include reporting of feature construction and tolerancing operations based on the ANSI Y14.5 Geometric Dimensioning and Tolerancing Standard. Results are manipulated and reported in spreadsheet form. The laser tracker 3-D measuring system features are presented for comparison in Table I.

APPLICATIONS TO SHIP PRODUCTION AND REPAIR

The applications of each technology to ship production and repair are only limited by the ingenuity of the potential user. Each 3-D computerized measuring system's software supports CAD and fairing programs for data exchange and comparison. The specific applications which follow provide evidence that accurate measurements, within the desired parameters, can be carried out by a single person in a shipyard environment.

Welding Research and Dimensional Control Using the Enhanced Theodolite System

The enhanced theodolite 3-D measuring system has been used extensively in support of the Marc Guardian• Tanker project. This double hull design has been developed by Metro Machine, Norfolk, VA, and Marinex International, Inc., Hoboken, NJ. The research has been supported by The Carderock Division of the Naval Surface Warfare Center.

The double hull sub-assemblies incorporate

FEATURE	ENHANCED ELECTRONIC THEODOLITE	LASER TRACKING INTERFEROMETER
Distance Measurement Sensor	Electro-Optical with modulated near-infrared light emitting diode	Servo motor driven helium-neon laser interferometer
Optic	Telescope, coaxial llight transmitting and receiving optic	Beam expander, Afocal, monolithic reflector
Distance Measuring Time	Static,one observation each 6 to 9 seconds	Continuous, 1000 points per second dynamic
Targeting	Microprism reflective disposable or tooling targets	Corner cube retroreflector positioned to .0005 to target feature
Measuring Range	100 meters (328 ft)	30 meters (100 ft)
Accuracy	±(1mm + 2ppm •Distance)	$1/10^6$ • Distance
Power	6-12 VDC Std, 110/115 VAC Opt	115/230 Volts AC
System Weight	15.8 - 22.6 Kg (35 - 50 lb)	38.5 - 45.3 Kg (85 - 100 lb)
Set up time to begin making measurements	5 to 10 minutes	15 to 30 minutes (plus warm up time of 30 minutes (minimum)
Approximate Cost (1994 Dollars)	$35,000 to $50,000	$140,000 to $180,000

Table I Feature Comparison, Laser Tracking Interferometer and Enhanced Electronic Theodolite

2.4m (8 ft) wide by 152 m (50 ft) long slightly curved shell plates in place of typically used flat plates. The curvature design, less than .15 m (3 ft) over the 2.4 m (8 ft) width, increases the resistance to deformation, thereby eliminating the need for longitudinal stiffeners other than along the shell plate edges. A reduction in structure weight, welding and fitting is achieved by this proprietary design. Structure welding is done with an automated welding process, simultaneously welding the inner and outer hull plates along the 15.2 m (50 ft) length of a 2.1 m (7 ft) high stiffener. The standard modular 2.1 m (7 ft) by 2.4 m (8 ft) by 15.2 m (50 ft) cubicles are then incorporated into 136-317 metric ton (150-350 ton) double hull subassemblies up to 61 m (200 ft) wide by 305 m (100 ft) high by 15.2 m (50 ft) long modules.

The enhanced the odolite 3-D measuring system was used to provide data regarding shrinkage of the shell and stiffener plates during the automated welding process. This data was required to engineer the final design dimensions of the shell and stiffener plates to meet a desired cubical dimensional control of ± .8 mm (± 1/32 in) and module dimensional control of ± 3.1 mm (± 1/8 in). Normally, during this measurement process, over 100 points of interest per hour were observed and recorded for later analysis by a single system operator.

This 3-D measuring system was also used daily to construct welding towers for the massive module assemblies, position 6.4-45 metric ton (4-5 ton) shell and girder plates into the fixture, provide verification of dimensional control prior to welding, and provide as-built dimensions of cubicle sub-assemblies for computer modeling of sub-assembly fits to complete the modules.

Inspection of Carrier Catapult Control Monuments Using the Laser Tracker

Newport News Shipbuilding, Newport News, VA, has contracted for the laser tracking to execute their highly accurate control surveys for their aircraft carrier catapult alignments since 1991. The catapult troughs are over 76 m (250 ft) in length, about 1.5 m (5 ft)wide and set below the carrier deck surface about l.2 m (4 ft).

Accurate measurements by conventional techniques is nearly impossible given the geometry of the trough, the pitch and roll of the ship and the working environment. The laser tracker measurements are taken after sundown, to eliminate the effects of the sun on the ship structure. Measurements must be made within time Constraints to eliminate the effects of extreme temperature fluctuations during the measurement process. Nearly 50 control monuments are measured for each catapult. The control monuments are nominally in line, vertically and horizontally. The in-line measurement capability of the laser tracker allows highly precise and efficient collection and analysis of the required data

Evidence to support the accuracy of the technology and procedure employed is supported by a comparison of data gathered during two different control surveys of the same catapult. An initial survey was accomplished in the summer of 1991, and another survey of the same catapult was completed during the winter of 1993. The largest RMS residual error of the three-dimensional coordinates between the two data sets was 25 mm (0.010 in) over the 85 m (280 ft) survey.

Conclusion

The availability and value of increased accuracy control through emerging technology should not be overlooked by the ship production industry. It has been shown that precision 3-D accuracy control leads to fewer man hours to accomplish specific fabrication, machining or positioning tasks thereby increasing productivity. Residual benefits can include less re-work, trimming, fitting and immediate comparison of as-built with design values. Quality **assurance procedures are easily documented and stored** on disk.

Measurements of large objects can be performed by a single system operator with the measurement systems described herein. The operator need not be highly skilled in engineering or computer techniques to perform accurate measurements. End product knowledge, training, aptitude, common sense and a desire to apply new technologies will lead to increased productivity.

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