COMBINED USE OF TOTAL STATION AND ARTICULATED ARM COORDINATE MEASURING MACHINE ON LARGE SCALE METROLOGY APPLICATIONS

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Abstract – The potential use of an hybrid system that combines a Total Station and an Articulated Arm CMM by utilizing a commonly-used industrial accessory, the hidden point bar tool, is examined. The analysis is focused on the formulation of the mathematical model that allows the interconnection of the two systems, the development of a traceable methodology frame and the transformation of data in a common reference system. The approach is experimentally verified on a typical industrial large scale component that is manufactured on the premises of Hellenic Shipyards S.A.

Keywords: Industrial Total Station, Articulated Arm CMM, Large Scale Metrology

1. INTRODUCTION

In a growing range of large scale industrial applications, tight Geometrical and Dimensional Tolerances (GD&T) are specified in order to establish the production of techno-economical robust constructions, mechanical components and assemblies. In that framework, dimensional metrology is considered as a key manufacturing process [1]. The objective of GD&T compliance assessment is to safeguard that the final product can be assembled and will meet the necessary functional and interchangeability requirements. Therefore, conformance with GD&T specifications must be verified during the inspection phase by the use of one or more appropriately selected metrology systems.

Focusing on large scale industrial applications, the particular requirements and the diverse nature of commonly met measurement tasks impose the utilization of several alternative metrological techniques and methods. For that purpose a wide range of metrology instruments is considered, such as Cartesian and/ or non-Cartesian Coordinate Measuring Machines (CMM), laser trackers, optical and laser scanners, digital imaging total stations, indoor GPS, digital photogrammetry – based tools etc [14-15]. The development of metrology instruments for Large Scale Dimensional Metrology (LSDM) applications that combine ergonomy, fast data acquisition / processing and high reliability is nowadays a fast – growing technological sector [2]. An analytical review of the existing technical literature and a systematic presentation of the academic state of the art in the field of LSDM are provided by [3] and [4].

Considerable variation in the parameters that are involved in common large scale measurement tasks (inspected component overall size and weight, type and range of accuracy specifications, physical access of the component, number of components to be inspected, etc.) make the final decision on the most appropriate metrology system rather complicated [1], [2]. With a growing number of competing technologies in the market, each of the available metrology instruments offers specific advantages and – as well as – major disadvantages for a given measurement task. Nevertheless, due to their inherent limitations, none of the currently available instruments can be considered as universally suitable for all types of LSDM tasks. In that context, recent research works address the need of hybrid measuring systems development [3]. Published literature in that topic is still quite limited and is mainly focused on hybrid systems that are implementing multi-sensor data fusion techniques, e.g. [5 – 7]. Research on the implementation of hybrid instrument fusion also addresses the potential integration of components derived from multiple technologies, e.g. 3D laser scanning and photogrammetry, [8], and the optimum combination of the advantageous technical characteristics for each instrument in order to accomplish specific targets, [9].

This paper studies the potential use of a hybrid system that combines an Industrial Total Station and an Articulated Arm CMM by utilizing a commonly-used industrial accessory, the hidden point bar tool. To the extent of the authors' knowledge, the combined use of the above metrology systems has not yet been addressed in published technical literature. The analysis is focused on the formulation of the mathematical model that allows the interconnection of the two systems, the development of a traceable methodology frame and the transformation of data in a common reference system. The approach is

experimentally verified on a typical industrial large scale component that is manufactured on the premises of Hellenic Shipyards S.A. The major conclusions are finally outlined and the key concerns of future research on that topic are presented and discussed.

2. COMBINED USE OF TOTAL STATION AND ARTICULATED ARM CMM: METHODOLOGICAL FRAMEWORK

Industrial Total Stations (ITS) and Articulated Arm CMMs (AA-CMM) are currently among the most widely utilized metrology systems for the effective GD&T inspection of industrial components and constructions on large scale metrology applications [1].

ITS are based on angle encoders and electronic distance measuring systems to capture the exact angle and distance portions for the further 3D point positioning on a specific reference system. Retro-reflective tapes and specialized reflectors with relevant mounts are used in order to direct or indirect measuring the object of interest (hidden point bar case). The coverage of vast work volumes (> 300 m) is one of the most crucial technical characteristic of these geodetic sensors. However, the heterogeneous distance accuracy compared with the angle uncertainty lowers the final produced point uncertainty (> ± 0.3 mm depending on the used method).

The basic working principle of AA-CMMs is depended on high-precision angular encoders that link a set of articulated arms. The rotary transducers measure the rotation of one arm with reference to another and, through multiple transformations, conclude to the final 3D coordinates of the hard, touch-trigger, or scanning probe, mounted at the end of the last arm [10], [11]. High-level flexibility and portability is considered as the major advantage of the AA-CMMs (in contrast to the typical bridge type CMMs), in conjunction with easy handling - ergonomy that allows for their positioning directly on the site of the object which is going to be inspected. Point uncertainty of their working volume begins where the most accurate ITS stop (typically < ± 0.1 mm for hard probes).

The combined use of both metrological instruments is mathematically ensured by the 'somewhat' implementation and measurement of homologous control points. On this paper, hidden point bar tool is examined as a possible solution. Hidden point bars are developed especially for Total Stations and photogrammetry where through the measurement of 2 - 5 collinear and coplanar retro - reflective targets, the coordinates of a hidden point are calculated (here 5 targets). The final point uncertainty of hidden point is comparable with the average standard deviation on a typical reflector target (± 0.3 mm) [12].

Hidden point bars are apparently not designed for use on AA-CMMs. However, in the proposed methodology the desired "control point", which is the point on the tip of the hidden point bar, is geometrically constructed by the AA-CMM. The intersection between the hidden point bar axis (cylindrical shape) and the local plane near the bar tip is the point of interest (Fig. 1). That point is homologous with the one which is produced from the normal use of the tool with

the ITS. The error sources for that method are mainly the form deviations of both the hidden point bar cylinder and the local plane of a special plate. For that reason, the form deviations of the main body of hidden point bar and the special plane plate were measured on a high-accuracy bridge type CMM (TESA Micro – Hite 3D-DCC, MPE_E ±0.007 mm) with RMS results better than 0.08 mm.
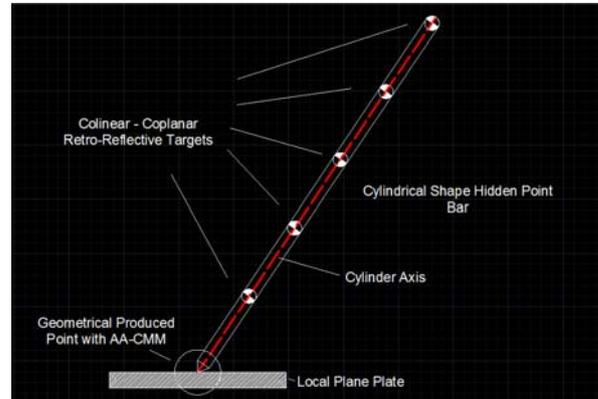

Fig. 1. Measurement of the hidden point bar tool with the AA-CMM

The generalized methodological frame for the combined usage is below briefly outlined:

- *Optimization, measurement and adjustment of a geodetic network with ITS.*
- *Placement of hidden point bar over the special plate and on several places inside the working volume of a specific setup AA- CMM.*
- *Geometrical creation of homologous points with AA-CMM and on each hidden point bar position.*
- *Mathematical Transformation from the local reference system of AA-CMM to that of the geodetic network.*
- *Further raw data processing*

3. MATHEMATICAL - STOCHASTIC MODEL OF OBSERVATIONS

Articulated arm and Total Station measurements have a considerable difference and characteristics on the final produced uncertainty. AA-CMMs typically have a volumetric uncertainty better than 0.08 mm all over the spherical space of their working volume. In the case of Total Stations, the point error ellipsis magnitude and direction is clearly dependant from the distance and the established coordinate system [13]. The point uncertainties are estimated from the law of error propagation and have values of 0.2 - 0.3 mm.

In this case is not examined the sensor fusion (with relevant uncertainty enhancement) but the transformation of measurements from articulated arms to total system reference system through homologous points. 3D Rigid similarity transformation is chosen as mathematical model where by using the least squares method, the best estimations of translations and rotations are calculated.

Scale is preserved because the deformation of AA-CMM measurements is not desirable.

The well known equation of the mathematic model is the following:

$$\begin{pmatrix} X^a \\ Y^a \\ Z^a \end{pmatrix} = m * R \begin{pmatrix} x^b \\ y^b \\ z^b \end{pmatrix} + \begin{pmatrix} t_x \\ t_y \\ t_z \end{pmatrix} \quad (1)$$

where m is the scale parameter (here m = 1), R is the orthogonal rotation 3X3 matrix, t_x, t_y, t_z are the translation components, x^b, y^b, z^b are the coordinates on articulated arm reference system (known quantities without error as a stochastic assumption) and X^a, Y^a, Z^a are the coordinates on total station reference system.

Least square adjustment method is followed where the best estimations of unknown transformation parameters, the a-posteriori variance of unit weight and variance - covariance matrices are determined.

4. APPLICATION EXAMPLE

The presented methodological framework and mathematical model were experimentally verified on a real-world, industrial application example. For the manufacturing of a high-accuracy welded/machined support framework, a critical sub-assembly that is integrated on a tight –toleranced metallic structure, a welding fixture was designed and manufactured in the premises of Helenic Shipwards S.A., Fig. 2. The geometrical and dimensional deviations of the welding fixture have a direct impact on the conformance of the GD&T specifications of the welded support framework and subsequently on the quality and performance of the overall metallic structure.

Fig. 2. Overview of the application example component.

The ITS that was used in the experimental setup was a Leica TDA 5005 (standard deviations (1σ - ISO 17123-3/4) for angles: 0.5´´ / for distances 0.5 mm on retro - reflective targets). Moreover, the AA-CMM was a Romer Arm, model Omega 2030, manufactured by Hexagon Metrology. The Arm has a spherical measuring range of diameter 3000mm

and its' accuracy is ± 0.07 mm, as per ANSI B89.4.22 - 2004. A hard probe with a 6mm spherical tip was integrated in the AA-CMM, Fig.3. The raw data recording and best fit analysis took place on specialized industrial metrology software's such as PC-DMIS v. 2013MR1 by Wilcox Assoc. - Hexagon Metrology (AA-CMM) and Axyz Leica CDM v.1.4.1 (ITS). The mathematical processing of measurements from both sensors had been held on a customized programming platform on Matlab R2009b.

Fig. 3. Measurement of the hidden point bar tool with the AA-CMM for further transformation to common coordinate system with ITS.

The connection between the two reference systems was realized through the creation and measurement of 5 homologous points. That 'homology' was shaped by the indirect measurement of the 5 targets of the bar (ITS) and from the intersection of cylinder axis and local plane (AA-CMM) as described on section 2 (Fig. 4).
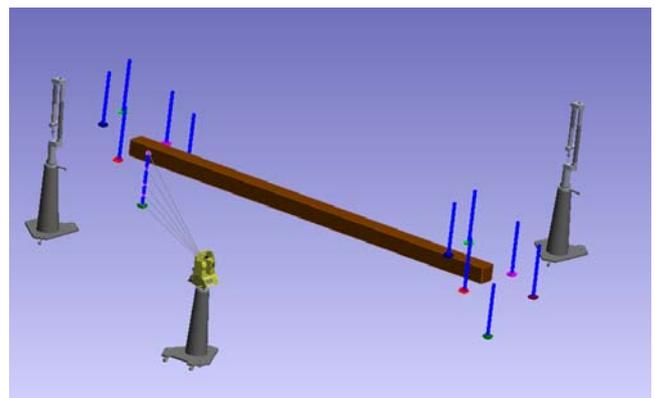

Fig. 4. Graphic illustration of the Total Station and AA-CMM placement around the application example component.

Least square adjustment method was followed. The transformation results were satisfactorily. Maximum residuals from the relevant matrix did not exceeded 0.2 mm and $RMS_{residual}$ = 0.19 mm. The a-posteriori variance of unit weight was $\hat{\sigma}_o$ = 1.02. The final measurements of AA-CMM were transformed to the global object coordinate system for further analysis.

5. CONCLUSIONS AND OUTLOOK

The methodological framework and the mathematical model briefly outlined in this paper aim at the effective, combined use of ITS and AA-CMM on large scale industrial metrology applications. The interconnection of the two metrology systems is currently achieved through the use of the hidden point bar tool that allows for the construction of homologous points and, eventually, the transformation of data in a common reference system. The suggested methodology and mathematical model have been experimentally verified on a typical measurement task for a real-world large scale mechanical component. The so far obtained results encourage further research and refinement of the approach through the consideration of a broader range of measurement tasks on complex industrial components and assemblies. Further research is currently focused (i) on the analysis of the traceability issues of the methodology, (ii) on the experimental use of dedicated and/or alternative artifacts for the creation of homologous points that allow for the interconnection of the two systems, such as spherical prisms of the CCR and BRR type, (iii) on the thorough mathematical modeling of the most significant uncertainty factors, (iv) on the potential use of Monte Carlo simulation techniques for the control of measured points uncertainly and finally (v) on the development of a common ITS - AA/CMM computational platform for the automatic analysis and adjustment of the data taken during their combined use through a commercially available GUI.

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