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# Enhancing the accuracy of high-speed laser triangulation measurement of freeform parts at elevated temperature

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Geometrical distortions due to inappropriate setting of process parameters are one of the main causes of variability in manufacturing hot forged thin parts. Their identification and measurement at the earliest steps of the process chain may permit well-timed setting of the process parameters, with significant benefit in case of small batch production.

The paper presents a Coordinate Measuring System for fast inspection of freeform parts at elevated temperatures through high-speed laser triangulation using multiple sensors. Main error sources are discussed, including a new method for the correction of systematic errors due to imperfect laser planes alignment. A procedure for testing the metrological performances at elevated temperature is also presented.

Metrology, Manufacturing, Forging

## 1. Introduction

The geometrical distortions of hot forged components are one of the most significant phenomena that influence variability of manufacturing process chains, making often necessary additional and costly operations such as re-heating steps, straightening in dedicated benches and machining. Despite this problem concerns many products and steps of the manufacturing chain, the most critical conditions are those suffered by thinner freeform shapes during the cooling phases, due to the plastic deformation induced by thermal gradients and to transformation plasticity effects as a consequence of the microstructure changes [1, 2].

Ideally, the estimation of the distortions should be made from the earliest stages of the process design, in order to select the most appropriate process parameters that minimize the number of subsequent operations. In particular for non-continuous and small-batch productions, accurate measurements at elevated temperature and reliable devices for the in-line evaluation of the geometric changes are crucial for both the prompt adjustment of the parameters and the process control.

The problem of measuring metallic parts at elevated temperatures is commonly addressed by optical technologies, with the advantage of making the measurement fast, therefore minimizing the change of temperature during the measurement and granting the required safety conditions for the operators [3]. Currently, three measuring principles are most commonly used for measurements at elevated temperature: (i) time-of-flight (TOF), (ii) image processing and (iii) triangulation.

The TOF measurement procedure uses a range imaging camera system that resolves the distance based on the known speed of light, measuring the round trip travel time between the camera and the subject for each point of the image. Grown in importance in the 2000s, such technology is used for the measurement of large parts [4-6], usually over 1 m, due to limited lateral resolution and overall accuracy for smaller parts.

The second approach comprises any form of signal processing for which the input is an image and the output may be either an image or a set of values extracted from the image. This method is limited to 2D measurements; i.e. it allows measuring lateral dimensions, but it does not give the possibility to evaluate depth in the case of complex shapes measurement [7, 8].

Triangulation methods refer to the process of determining points in 3D space, by using multiple sensors, possibly a structured light source and a known spatial relationship between them. Laser triangulation measurements at elevated temperatures have been implemented with different setups [9-13]. It was demonstrated that the use of fixed sensors [9-12] may allow better accuracy than moving the sensor while measuring [13], and that noise due to temperature effects (e.g. part radiation) can be reduced by using optical bandpass filters. Through optical multi-sensor-measurement system, Bernstein et al. [9-10] demonstrated the possibility to measure extruded profiles up to a diameter of 100 mm and a temperature of 820 °C with accuracy in the range of 0.05 mm.

A more detailed review of measuring systems for hot workpieces is given in [14]. However, these systems were developed for components with constant cross-section, and not for acquiring the complete 3D geometry of freeform shaped parts at elevated temperatures.

This paper presents a newly developed procedure to improve the accuracy of a Coordinate Measuring System (CMS) based on multiple laser scanning triangulation sensors [14], capable of measuring the geometry of complex-shaped parts at temperatures up to 1200 °C in less than 10 s. The aim is to measure workpiece dimensions at the actual temperature and use this information for numerical simulations of the forging and cooling processes, taking into account both thermal expansion and microstructure changes due to material phase transformation effects. Therefore, measurement results obtained using the CMS on hot parts are not corrected to 20 °C [15].

The target value of the Maximum Permissible Error (MPE) for bidirectional length measurements on the prototype CMS was set to 0.2 mm. The CMS is described in Section 2, while modelling and correction of most relevant systematic errors are presented in Section 3, where quantification and correction of imperfect laser planes alignment is addressed. Finally, in Section 4, a procedure for testing the length measurement performance at elevated temperature is discussed.

## 2. Measuring system description

The prototype CMS is composed of two main subsystems: a 2D scanner by Zumbach Electronic AG [16] and a custom linear axis. The scanner acquires 2D cross-sections (xy-plane) of the workpiece by means of laser line triangulation. The linear axis moves the piece through the 2D scanner along the z-axis and is provided with a magnetic scale of 2 µm resolution. A magnetic scale was chosen because of the harsh shop floor conditions.

From cross-sections and z-axis positions, a 3D model is generated using a customized meshing algorithm based on [17]. Figure 1 shows a model of the system, while a summary of main technical data is available in Table 1.

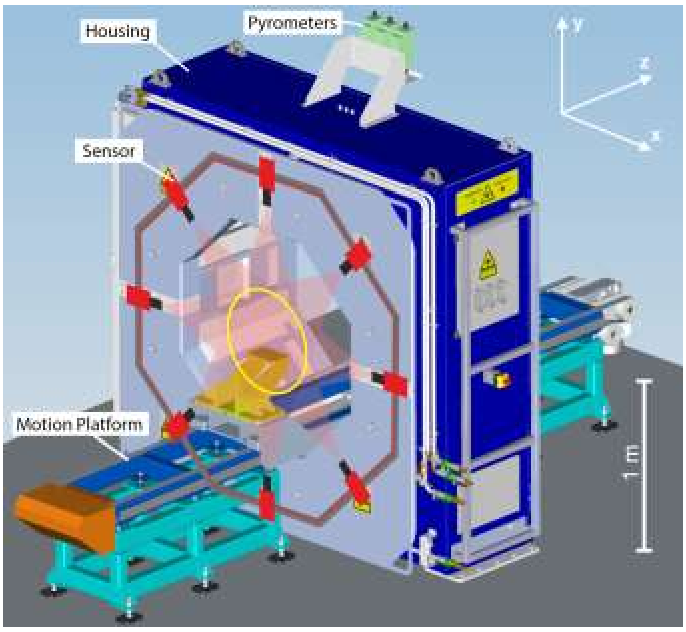

**Figure 1.** CAD model of the CMS. Overlaid a sketch of the metrology frame, with laser planes shown in light red, measurement area of ⌀ 800 mm shown by yellow circle.

The 2D scanner has modular design and can use up to eight light-sectioning sensors. Each sensor, consisting of a line laser, a CMOS camera and optical bandpass filter, is arranged on an octagonal metrology frame to obtain complete profiles even in case of concave cross-sections. To keep the sensors free from dust in the harsh shop floor environment, an integrated blowing system is providing a constant flow of clean air in front of each of the sensor windows. Pt100 temperature sensors are installed on the top of the octagonal frame, on the housing and inside the housing to monitor internal air temperature. Special attention was given to the thermal insulation of the metrology frame from the heat radiation caused by the hot workpieces.

Workpiece temperature is measured at each cross-section by multiple pyrometers (optris CTlaser 3M [18]) mounted on top of the system (see Fig. 1).

**Table 1.** Summary of main technical data of the prototype CMS.

| Characteristic | Value |
|---|---|
| Dimensions (H x W x D) | 2.6 x 2.5 x 1 m |
| Measurement speed | 320 Hz, ~ 1 000 000 points/s (typical) |
| Measurement time | < 10 s (for 800 mm long parts) |
| Measurement area | ⌀ 800 mm |
| Sensor sampling distance | 0.3 mm (typical) |
| Sensor depth resolution | 0.03 mm (typical) |
| Internal air temperature | 20±1 °C |
| Pyrometer accuracy | ±(0.3% of reading + 2 °C) |

## 3. Modelling and correction of errors

The alignment of laser planes (i.e. coplanarity of laser curtains) and temperature effects on the CMS were found to be the two most important error contributors. The adjustment of laser planes is particularly difficult due to the large measurement area. The maximum error due to planes misalignment was quantified in 0.5 mm for distance measurements on steepest details on turbine blades, using a newly developed method that is used also for correcting such errors (section 3.2). The magnitude of temperature effects on the CMS was assessed by repeated measurements on a calibrated artefact during 30 minutes of operation with the temperature control disabled, showing errors up to 0.2 mm.

In addition, other error sources, e.g. vibration in forging plant, geometrical errors of the linear axis, were estimated and considered to be negligible in relation to the target MPE.

### *3.1. Temperature effects*

By the use of two conditioning systems – an air chiller and a water flow inside the octagonal frame – the internal temperature is controlled at 20±1 °C. In this way, temperature effects on the CMS could be reduced to 50 µm. Thermal stability was verified during eight hours of operation, while 10 hot workpieces were measured. The temperature influence on the sensor components (CMOS chip and focal length elongation) was estimated according to [19] for an upper bound of $\Delta T = 5$ °C with a resulting error of less than 10 µm. The heat radiation from the hot workpiece was found to have no direct influence on the raw image data. Due to the installed optical bandpass filters, the radiation effect on the image sensor lies below the threshold used for laser line detection while attenuating the laser signal by 10 %. The refraction of the laser light in air due to temperature gradient was also considered. Using the Ciddor equation [20] and a simplified model with a single refractive index change between sensor (30 °C) and workpiece (100 °C) yields a maximum error of 30 µm for distance measurements. Due to the relatively low influence of internal, external and sensor temperature residual deviations, these effects were not corrected.

### *3.2. Laser planes alignment*

Bernstein [9-10] investigated the influence of angular misalignments for 2D measurements on constant cross-sectional profiles with the conclusion that the influence of a 0.6 mm misalignment has negligible influence on measurements of constant cross-sectional profiles. Nevertheless, for non-constant cross-sectional profile workpieces this effect is more severe since the slope of the workpiece in z-direction directly affects its sensitivity. An offset of the planes along the z-axis results in datasets acquired at different positions, while an angular misalignment around the x- or y-axis will cause the datasets to be distorted.

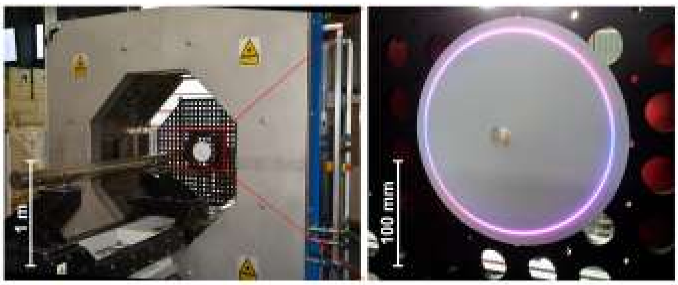

**Figure 2.** Left: photo of the system with cone artefact positioned inside the measurement area. Right: zoom on the artefact with enabled lasers.

Hereafter we describe a new method to estimate the sensor z-positions and x/y-orientations in order to minimize laser plane distances in the measurement area by adjusting them. We propose the use of a high-slope radially symmetric artefact, i.e. a conical sample. The sample artefact is made of aluminium and white coated to obtain an optically cooperative surface (Figure 2). The nominal half aperture angle is 74 degrees, this being the maximum steepness on typical workpieces to be measured. Sample conicity, perpendicularity of the cone axis to the base and flatness of the base were identified as relevant parameters for the successful implementation of the method and calibrated using a tactile CMM (MPE of length measurement: 2,7 + L(mm)/300 µm).

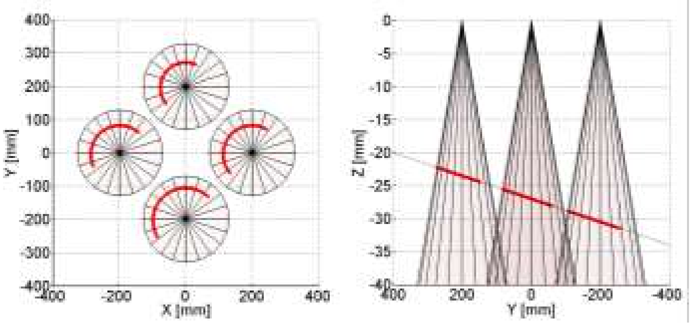

**Figure 3.** Intersections (red curves) between a single laser plane (1 degree tilt around x-axis) and the cone at four positions. Left: top view. Right: side view, z-axis magnified for better clarity.

Previously, both the internal (e.g. focal length, principle point) and external (position and orientation w.r.t. laser plane) camera parameters are calculated using available methods [21]. The sample is fixed at four known positions, where the laser plane light hits the cone surface (Figure 3). All resulting partial conics (i.e. partial ellipses) in the 2D laser plane space are then augmented to 3D and altogether rigidly transformed (z-position, x/y-orientation) to minimize their squared distance to the cone surface at all positions. The resulting transformation parameters describe the laser plane z-position and x/y-orientation relative to the cone positions. By using this information, mutual misalignments can be minimized in two ways: i) mechanical adjustment of sensors alignment, with lower bound given by the resolution of the adjustment procedure, and ii) software adjustment of the recorded points in a common coordinate system [22], resulting on more complex data generated by the CMS (i.e. 3D datasets) instead of simple 2D profiles. While the former procedure is preferable for constant cross-section parts, the 3D nature of the latter is well suited for freeform parts and, moreover, faster in the setup phase.

To demonstrate the accuracy improvement by the proposed procedure, several experiments were performed on parts featuring different geometry. In case of limited slope, the improvement is intrinsically small, while on steeper surfaces the advantage is evident: e.g. for the steepest details on turbine blades, typical deviations between measurements of two misaligned adjacent sensors were reduced using software correction from 0.5 mm to 0.1 mm (Figure 4) with 5-times improvement by the presented method.

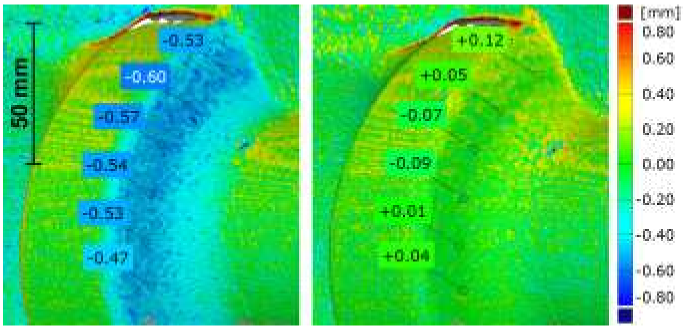

**Figure 4.** Deviation map of data coming from two different sensors on a turbine blade foot. Left: without plane correction. Right: with correction.

## 4. Testing

In order to test the improved metrological performance of the CMS by the proposed method, bidirectional length measurements were performed on a series of calibrated parts. For meaningful results, testing must be performed with environmental conditions as close as possible to those active while measuring actual workpieces. Therefore, experiments were performed at the forging plant of Pietro Rosa TBM s.r.l., Italy, where the CMS was available in the framework of the HOTGAUGE research project.

At the same time, for acceptable testing costs and testing uncertainty, the calibrated parts have to be not too expensive, with curved and optically cooperative surfaces, easy to calibrate with appropriate uncertainty and having small coefficient of thermal expansion (CTE). Experiments were then performed using commercially available 130x70x4 mm glass-ceramic plates (Schott Nextrema® [23]) with rounded surfaces in the smallest dimension, having a CTE of $(0.63 \pm 0.2) \cdot 10^{-6}$ $K^{-1}$ in the range 20-300 °C, as stated by the manufacturer. Calibration of the two main dimensions was performed using a scanning tactile CMM (MPE of length measurement = 2,7 + L(mm)/300 µm) with measurand definition, measuring strategy (i.e. area of interest and point density) and data processing similar to those active while measuring on the optical CMS, obtaining a calibration uncertainty lower than 5 µm.

To reach environmental conditions as close as possible to those active while measuring actual workpieces, a series of hot billets with mass similar to the typical turbine blade where individually loaded onto the CMS and moved back and forth as in normal operation for one hour. During this time, the average temperature of the billet was starting at approx. 850 °C and decreasing to approx. 400 °C before loading the next one. Then, eight calibrated glass-ceramic plates were loaded on a dedicated frame positioned above a hot billet at about 850 °C. The plates were fixed in two different orientations, in order to measure the two distinct calibrated lengths of 70 and 130 mm. Individual part alignment was on purpose slightly different, resulting in an angle of few degrees between moving direction and corresponding workpiece axis. The glass-ceramic plates and the hot billet were then measured continuously for 40 minutes, moving backwards and forwards, resulting in 50 measurements with billet temperature decreasing from approx. 800 to 300 °C.

Testing result of length measurements in hot condition are presented in Figure 6, showing deviations from the reference values well within the target MPE of the prototype CMS (0.2 mm).

Results are corrected for thermal expansion of the glass-ceramic plates, using individual average temperature data for each plate.

Dimensional stability of the plates was investigated after testing in hot conditions, obtaining deviations within the calibration uncertainty.

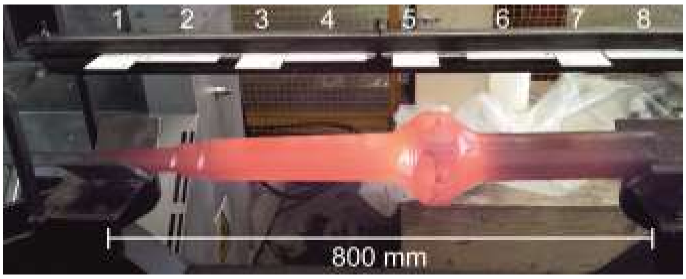

**Figure 5.** Photo of the glass-ceramic plates and hot billet during testing.

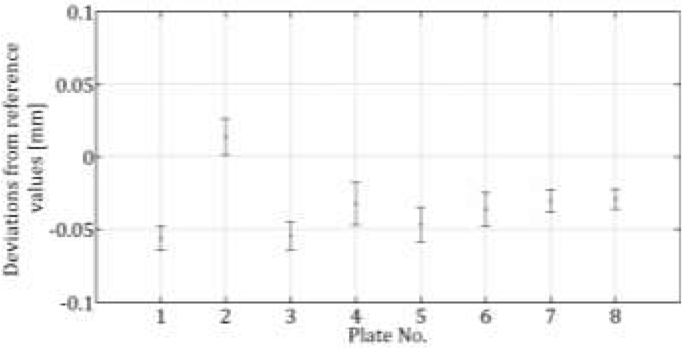

**Figure 6.** Results of testing in hot conditions. Even and odd plate numbers refer to glass-ceramic plates oriented to measure the 70 mm length and the 130 mm length respectively. Error bars represent the standard deviation of 50 repetitions.

Temperature of the glass-ceramic plates was not measurable by the available pyrometers, because of their partial transparency to the infrared wavelength; therefore, to estimate their temperature, a thermal computer simulation using ANSYS v.15 was performed. Radiation effects where simulated using the Gauss-Seidel radiosity solver method, assuming constant emissivity for both the billet and the plates. Maximum estimated temperatures of plates during testing are reported in Table 2, with room temperature of 30 °C. For practical reasons, a single correction value for thermal expansion was computed for each plate, using its average simulated temperature.

**Table 2.** Highest temperatures reached by the glass-ceramic plates during testing, as computed using FEM simulation.

| Plate No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Maximum plate temperature, °C | 106 | 126 | 131 | 143 | 152 | 150 | 136 | 106 |

CMS test uncertainty [24, 25] was then determined using information on plates calibration, CTE and temperature values as well as their uncertainty. Test uncertainty resulted to be 8.5 µm, well adequate for testing the MPE of the prototype CMS (0.2 mm).

## 5. Conclusions

The paper describes a newly developed CMS capable of measuring the geometry of complex-shape parts at temperatures up to 1200 °C in less than 10 s (for 800 mm long workpieces), using multiple laser scanning triangulation sensors. Main error sources (thermal effects and laser planes misalignment) were discussed, and a new method to reduce errors introduced by imperfect alignment of sensors was presented. The new method is based on a series of measurements on a conical sample, and allows automatic determination of adjustment parameters and data correction, yielding up to 5-times reduction of deviations between measurements of two misaligned adjacent sensors.

A new procedure for testing the prototype CMS in hot conditions was also presented. The procedure uses glass-ceramic plates, featuring low CTE and two calibrated lengths of 70 and 130 mm, mounted on a fixture over a hot billet. Test results demonstrate that the prototype CMS, after more than one hour of operation in hot conditions, is measuring with bidirectional length measurement errors in the order of 0.05 mm.

Test uncertainty was determined using calibration data, CTE and temperature information, resulting to be less than 9 µm.

## Acknowledgements

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## References

[1] Gur H.C., Tekkaya A.E., 2001, Numerical investigation of non-homogeneous plastic deformation in quenching process, Materials Science and Engineering A319–321 164–169.
[2] Bruschi, S., Ghiotti, A., 2008, Distortions induced in turbine blades by hot forging and cooling, Int. Journal of Machine Tools and Manufacture, 48 (7-8), pp. 761-767.
[3] Dworkin, S.B; Nye, T.J., 2006, Image processing for machine vision measurement of hot formed parts. J. of Materials Processing Technology 174 (1-3), pp. 1–6.
[4] He J. et al, 2012, Measure dimension of rotating large hot steel shell using pulse laser on PRRR robot. Measurement, 45(7):1814–1823.
[5] Du Y., et al., 2011, Measurement system for hot heavy forgings and its calibration. Optical Meas. Sys. for Industrial Inspection VII, pages 80822Y–80822Y–11. SPIE.
[6] Tian Z,, 2009, Dimension measurement of hot large forgings with a novel time-of-flight system. Int.J. of Advanced Manufacturing Technology, 44(1-2), pp. 125–132.
[7] Savio E., De Chiffre L., Schmitt R., 2007, Metrology of freeform shaped parts, CIRP Annals, 56/2:810-835.
[8] Carmignato S., et al., 2010, Metrological performance of optical coordinate measuring machines under industrial conditions. CIRP Annals, 59/1:497-500.
[9] Bernstein J. and Weckenmann A., 2012, Measurement uncertainty evaluation of optical multi-sensor-measurements, Measurement 45, pp. 2309–2320.
[10] Bernstein J. and Weckenmann A., 2011, User interface for optical multi-sensorial measurements at extruded profiles, Measurement 44:202–210.
[11] Stöbener, D. et al., 2003, Distance measurements with laser-triangulation in hot environments. XVII IMEKO World Congress. Dubrovnik, June 22-27, pp. 1898–1902.
[12] Wei L. et al, 2011, Fast dimensional measurement method and experiment of the forgings under high temperature. J. of Mat.Processing Tech. 211 (2) :237–244.
[13] Zhang Y., et al., 2014, Measurement and control technology of the size for large hot forgings. Measurement, 49:52–59.
[14] Schöch A., et al., 2014, Fast measurement of freeform parts at elevated temperature using laser-triangulation principle. In: 11th Laser Metrology for Precision Measurement and Inspection in Industry 2014, Tsukuba, Japan.
[15] ISO 1:2002: Geometrical Product Specifications (GPS) - Standard reference temperature for geometrical product specification and verification.
[16] Zumbach Electronic AG, www.zumbach.ch. Accessed January 2015.
[17] Chae, Lee, 1999, Volume triangulation from planar cross sections. Computers and Structures Volume 72, Number 1, pp. 93-108(16).
[18] Optris GmbH, www.optris.de. Accessed January 2015.
[19] Clarke, T.A., et al., 1991, Laser-based triangulation techniques in optical inspection of industrial structures. San Diego, 1 July: SPIE Proceedings pp. 474–486.
[20] Ciddor P. E., R. J. Hill, 1999, Refractive Index of Air. 2. Group Index. Applied Optics (Lasers, Photonics and Environmental Optics), 38, pp. 1663–1667.
[21] Hartley, R. I. and Zisserman, A., Multiple View Geometry in Computer Vision. Second Edition, 2004. Cambridge University Press, ISBN: 0521540518.
[22] Weckenmann, A.X. Jiang, K.-D. Sommer, U. Neuschaefer-Rube, J. Seewig, L. Shaw, and T. Estler. Multisensor data fusion in dimensional metrology.
CIRP Annals, 58(2):701–721.
[23] Schott AG, www.schott.com. Accessed January 2015.
[24] ISO/TS 23165:2006, Geometrical product specifications (GPS) - Guidelines for the evaluation of coordinate measuring machine (CMM) test uncertainty.
[25] Savio E., 2006, Uncertainty in testing the metrological performances of coordinate measuring machines, CIRP Annals, 55/1:535-538.