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Beam Straightness Measurement with Laser Triangulation System: a steel industry use case

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***Abstract* — With reference to a steel bars manufacturing process, there is a variety of factors which can contribute to defect generation such as geometrical non-conformity. Non-destructive Inspection systems (NDIs) are a key element for the early detection of defects in a production line.**

This paper considers a particular steel industry use case focusing on the design and development of an NDI system to measure the straightness of steel bars in line, by a non-intrusive approach. This NDI is based on the laser line triangulation technique, interacts with a robot and is connected to a software platform where additional services may be exposed.

The paper presents a parametric study of the laser line triangulation system to be developed, highlighting the influence of design parameters over system resolution and measurement range. Considering the use case this paper focuses on, the straightness deviation can be correctly estimated as the resolution value can be extremely fine: 0.01 mm if using subpixel accuracy.

The steel beam is ideally modelled as a parallelepiped, however in reality its shape can deviate: this causes uncertainty due to the model of the measurand. The paper then discusses this uncertainty and the one related to the misalignment of the laser plane with respect to the beam axis.

Results show erroneous estimation of the straightness deviation up to 1.8 mm in some cases of beam distortions analysed.

The simulation presented in the paper is therefore of primary importance to evaluate the factors which may influence the overall uncertainty of the straightness measurement process.

Keywords— Zero defect manufacturing, non-destructive inspection, in-line quality control, Industry 4.0, straightness, laser triangulation system, resolution, beam distortion

I. Introduction

Quality control is a key element in the context of Industry 4.0 to identify in advance possible defects which can occur along the production line. Moreover, it enhances production efficiency and efficacy because it leads to reduced defects and lower costs (due to less rework, fewer mistakes, and fewer delays), as well as a better use of machines and materials [1].

This paper focuses on a peculiar application of quality control to measure the straightness of steel bars using a laser triangulation system.

The measurement system is designed and implemented according to the paradigm of Zero-Defect Manufacturing (ZDM). ZDM aims to achieve zero defects in a production system: scrap reduction, lower production costs, shorter production times, higher productivity, and a higher resource and energy efficiency [2]. Considering global greenhouse gas emissions by sector in 2016, the iron and steel manufacturing industry is responsible for 7.2% of the total emissions [3]. Therefore, ZDM results a solution not only to reach higher quality of the product, but also to pursue a more sustainable production, by reducing energy and material waste and consequently CO_2 emissions. A Pareto analysis, on steel bar manufacturing process, revealed four major sources for process scrap: variation in the temperature range, input material composition, cutting blades life and water pressure during quenching [4]. Quality control systems are therefore of primary importance because they contribute to monitor and identify the parameters which are sources of process scrap with the aim to reduce it.

The measurement system design and implementation is part of an European Project called OpenZDM and it will be installed in the production line of VDL Weweler bv. which produces trailing arms for air suspensions of buses.

This paper presents in Chapter 2 the OpenZDM framework and its main goals focusing on the description of Non-Destructive Instruments (NDIs) for ZDM. Chapter 3 focuses on the description of the operating principle of the laser triangulation technology and how the resolution along the depth axis can be computed. A parametric study is also carried out considering different design parameters. Moreover, Chapter 4 presents the algorithm to perform a straightness measurement of a beam along with the analysis of possible beam distortions and how they can influence the straightness measurement. In Chapter 5 it is discussed how misalignment of the laser plane can affect the result of the measurement and make it more uncertain and lastly Chapter 6 conclusion and next steps are presented.

II. OpenZDM Framework

OpenZDM framework aims to provide an open platform to support production processes in cyber-physical manufacturing in the context of ZDM [5]. Its main scope is to

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instrument production lines with a series of Non-Destructive Inspection systems/techniques for quality assessment, which could provide data useful to monitor the process, perform quality control and build up a data model to understand the process and the origin of defects. The NDIs will use different technologies and will be applied at different stages of production line. OpenZDM framework involves five different pilots that have been selected in a complementary way. Section II C focuses on VDL Weweler bv. use case which is the pilot where the NDI considered in this paper will be implemented.

A. Non-Destructive Inspection Systems For Zero Defects

Ideally, ZDM aims for the complete elimination of defects, not simply through detection and correction of defective products and process parameters, but also through defect prediction and prevention [2]. Defect detection is performed thanks to NDI systems which measure the features of the product in line without contact and make a conformity assessment.

The NDI system is a measurement system integrated with data analysis and diagnosis, thus forming a quality control station. The data acquired in line from the sensors are then processed and shared becoming added-value information, thanks to the integration to the OpenZDM platform, which is used for online process control and adaptation.

B. Quality Control on incoming raw material

In multi-stage production systems, as a trailing arm production process, the earlier a defect is detected, the better: in fact, early identification of non-conformity, performed at a single process level, prevents defects from propagating to down-stream processes [6].

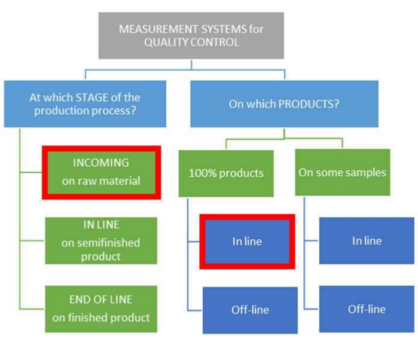

Fig. 1. Types of measurement systems for quality control

The NDI this paper focuses on measures the straightness of a raw metal bar at the very beginning of the production process and is applied on 100% products, as highlighted in red in Fig. 1 which describes the different types of measurement systems used in quality control. As the non-destructive inspection is carried out at the early stage of production on a raw material, this measurement technique can be applied to a variety of cases in the metal industry who deal with metal bars, not only in the trailing arm production use case.

C. VDL Weweler bv. use case

The NDI is designed to be applied in line in the production plant of VDL Weweler bv. which develops, produces, tests, and sells air suspension systems, axle lift systems and parabolic springs from its fully automated plant in Apeldoorn (NL) [7]. In this plant, improvements to in-line quality control are continuously implemented.

Possible defects in trailing arm production process are related to the straightness of the arm, the thickness of the steel bars and surface defects. Nevertheless, a preliminary analysis on the raw product is necessary because the incoming material itself may include defects that become apparent during the following heating and machining processes.

III. Materials and Methods

This chapter describes firstly the laser triangulation system technology focusing on the use case of straightness measurement of steel bars. Designing a triangulation system to detect a target object about 1 m long is not easy and requires a parametric study to choose the proper value of the main parameters which influence the resolution along the depth axis which is the Z-axis of the laser. This paper focuses on variation of angle of triangulation, X-Field of View (X-FOV), laser stand-off distance and sensor and how they affect the Z-resolution value.

A. NDI Based On A Laser Line Triangulation System

The NDI this paper focuses on is based on a laser triangulation system which will be applied to detect and measure the straightness of a metal beam. As the industrial environment is hostile, the non-contact measurement technique proves to be efficient. The camera is positioned over the laser and inclined downwards to reduce deposition of dust on the lens.

In the application (see Fig. 2), the camera and the laser are fixed on a support bar while the steel beam is placed by the robot in front of the sensor and aligned to the laser plane with the longer axis of the beam in the plane X'Z' as it can be seen from Fig. 2. The robot holds the bar by a magnetic gripper. The robot keeps the bar steady to perform a first profile measurement with Z'-axis of the bar as the depth axis, then rotates the bar along its X'-axis in order to perform another measurement of the bar (with Y'-axis of the bar as the depth axis) and detect straightness on both X'Z' plane and Y'Z' plane.

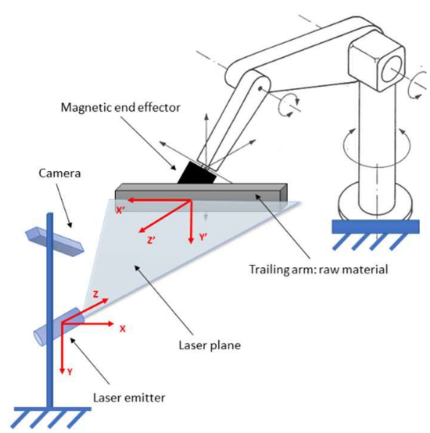

Fig. 2. NDI for straightness measurement of steel bars

The NDI system is therefore composed of two assets (the laser triangulation system and the robot) that interact and cooperate in the specific task. In particular, the robot triggers the laser triangulation system to acquire the two profiles for each bar, picks up the bar from the line and puts it back once the measurement is completed.

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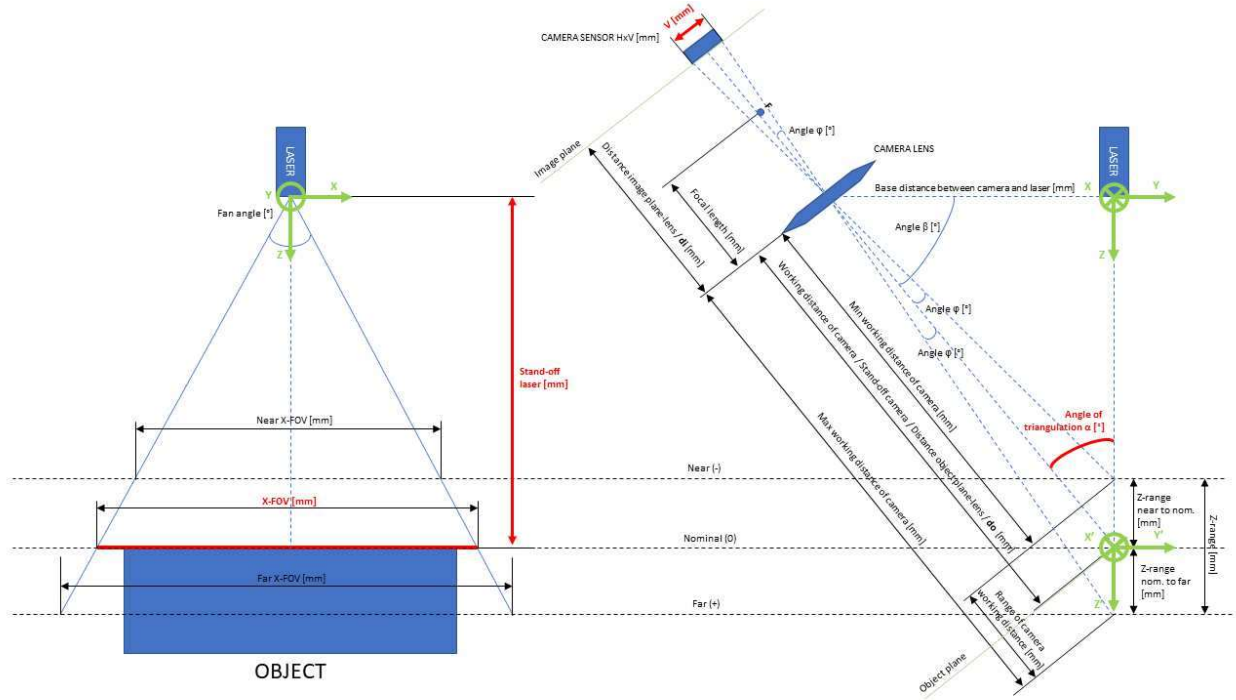

Fig. 3 Design of a laser line triangulation system

B. *Design Of A Laser Line Triangulation System*

When designing a laser triangulation system several different parameters need to be taken into account. The laser plane needs to include the dimension of the object to be detected while the camera sensor field of view needs to contain the laser line projected.

Considering straightness measurement of a metal beam, the X-FOV (Field of View along the X direction) to be considered needs to be long at least as the bar length which is about 1 m. A value of 1200 mm is chosen, which is challenging in laser triangulation systems that usually deal with much smaller X-FOV.

The angle of triangulation is fixed at 45° and the stand-off distance of the laser is set at 1000 mm. This represents a compromise between high Z-resolution value and acceptable base distance between the camera and the laser. To increase Z-resolution, a higher triangulation angle or higher stand-off of the laser is needed. However, increasing the angle would imply a longer base distance between the camera and the laser which cannot be accepted as the two elements need to be mounted on a physical support in a production line, so overall dimensions need to be taken into account. Same considerations for a higher stand-off value which would also imply a lower SNR (Signal to Noise Ratio) at image level.

For the use case considered, the expected straightness deviation to detect are 1-2 mm so the measurement system should have a Z-resolution around 0.1-0.2 mm.

Regarding the laser system configuration, the two main options that can be adopted are laser aligned or camera aligned (Fig. 4). Despite option with camera aligned allows to obtain better sensor sensitivity and Z-resolution, there are different drawbacks, for example the thickness profile is measured at different position y, depending on the local thickness z [9]. For this reason, we chose the option with laser aligned because it allows the measurement to be always the same along the XZ section.

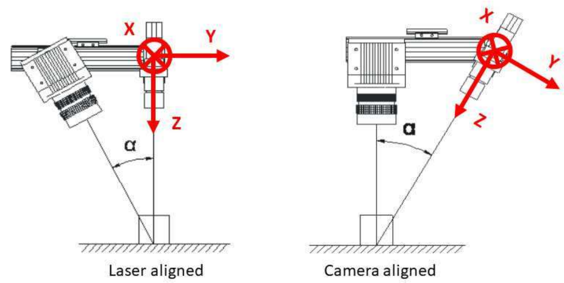

Fig. 4. Triangulation system configuration [8]

C. *Parametric Z-Resolution definition*

The Z-resolution of the system depends on different parameters, and it is not constant across the measurement range.

A laser triangulation system is an imaging system, therefore while moving from 2-D camera coordinates to 3-D world coordinates, the accuracy of the estimated 3-D coordinates of a point in space will be limited by the image resolution. Therefore, algorithms that estimate feature position to subpixel accuracy by interpolating the sensor response function are useful [9].

In this paper a parametric study is performed on the Z-resolution value computing also the resolution at subpixel accuracy which can reduce the Z-resolution by 1/64, if the subpixel factor chosen is six.

The parametric study is performed varying the parameters highlighted in red in Fig. 3 and reported in Table 1. The second set of parameters is the one chosen for the case study.

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Table 1 Parameters of the parametric study

Parameter	Set 1	Set 2	Set 3
ANGLE OF TRIANGULATION	30	45	60
X-FOV	1000	1200	1400
LASER STAND-OFF DISTANCE	800	1000	1200
SENSOR	1280x1024 6.6 µm/pixel	2048x1088 5.5 µm/pixel	4096x3072 5.5 µm/pixel

Fig. 5 represents the Z-resolution versus position z' of the point scanned in the reference system highlighted in green in Fig. 3. At a stand-off of 1000 mm (posizion z'=0) the Z-resolution value is around 0.83 mm and decreases to 0.01 mm considering the subpixeling. Considering the application of straightness measurement, which requires to detect deviations as small as 0.1-0.2 mm, the Z-resolution is adequate only if subpixel interpolation is used (0.01mm). The measurement range along Z is around 370 mm in the near field and around 580 mm in the far field with a total Z-range of 950 mm.

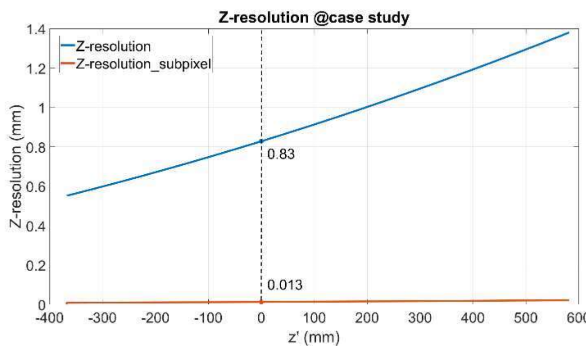

Fig. 5. Z-resolution curve @case_study

Fig. 6 represents the parametric study on the angle of triangulation considering all the other parameters fixed at the values of the second set. As expected, the Z-resolution decreases as the angle of triangulation increases but also the Z-range (z') decreases. This means the system has better resolution but on a smaller measurement range along the Z-axis.

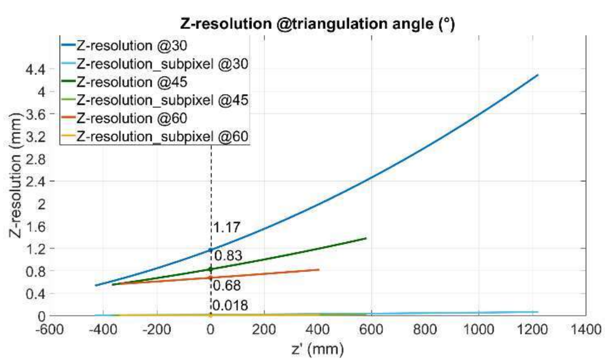

Fig. 6. Z-resolution curve @triangulation_angle

Fig. 7 represents the variation of the Z-resolution at different X-FOV values which means different object size to be detected. The measurement of larger objects implies larger Z-resolution value which means lower performances of the laser scanner.

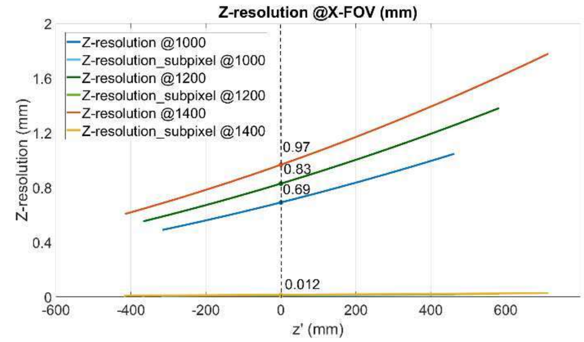

Fig. 7. Z-resolution curve @X-FOV

Fig. 8 shows the dependence of Z-resolution over position z' in the measurement range for three different stand-off distances (800, 1000, 1200 mm). If stand-off distance increases, then Z-resolution increases in the near field and decreases in the far field.

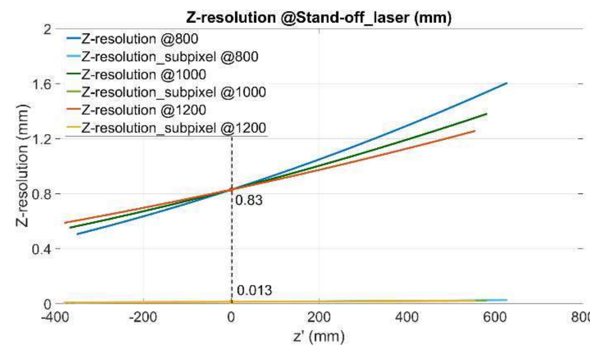

Fig. 8. Z-resolution curve @Stand-off_laser

The sensor dimension strongly influences the Z-resolution value; Fig. 9 shows different sensors and it is clear how the resolution gets better reaching a value of 0.4 mm at the stand-off with the 4096x3072 pixel sensor which is the largest with 22.5x16.90 mm dimensions. Considering the requirements, a subpixel accuracy would be needed anyway to reach values lower than 0.1-0.2 mm.

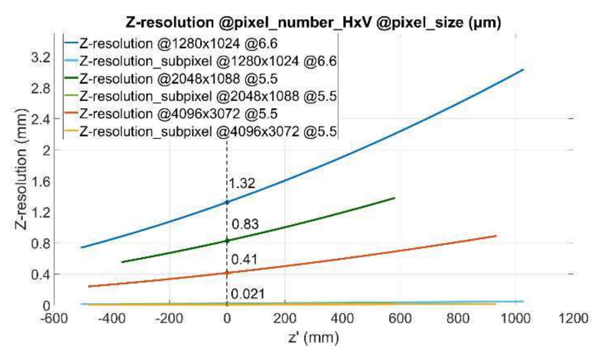

Fig. 9. Z-resolution curve @pixel_number_HxV @pixel_size

IV. STRAIGHTNESS MEASUREMENT

This chapter focuses on the straightness measurement analyzing the algorithm to calculate the straightness deviation and exploring different uncertainty sources influencing the straightness measurement, in particular beam distortions and laser plane misalignment.

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A. Straightness Measurement Algorithm

The laser line extraction algorithm is camera embedded. The software routine implements then a pixel to mm conversion based on the calibration of the laser line triangulation system and finally performs the detrending of the laser line, to eliminate a possible misalignment of the system with respect to the bar in the XY plane. Then a polynomial fitting is performed, and the straightness deviation calculated. Lastly a conformity assessment is performed with respect to given specifications, and a diagnosis is carried out, to assess if the straightness deviation measured respects the tolerances required. In all this procedure, the straight beam is considered to be a parallelepiped and the deviation from straightness related only to pure bending.

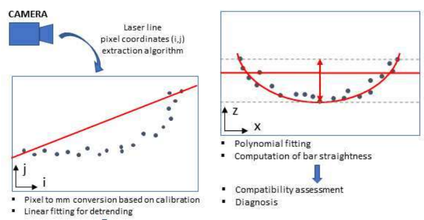

Fig. 10. Software routine for straightness measurement

B. Types Of Possible Beam Distortions

In reality, the measurand (the steel beam) may differ from its ideal model. Indeed, the steel beam, which is the product considered in this use case, does not always conform to the ideal shape of a parallelepiped, but different distortions can be found. Fig. 11 summarizes different possible distortions of a beam in a simplified way. To be noted that the reference system has the X-axis along the length of the beam, the Y-axis along the width and the Z-axis along the thickness. Bar dimensions are fixed as: length 1000 mm, width 100 mm, thickness 50 mm.

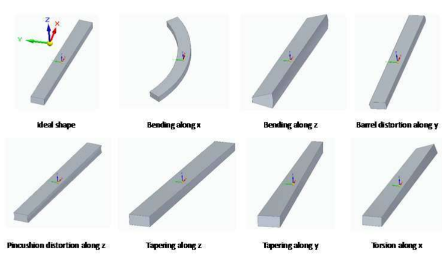

Fig. 11. Possible distortions of a beam

V. Analysis Of The Influence Of Beam Distortions On Straightness Measurements

The following section focuses on a simulation analysis to study how beam distortions and misalignment of the laser plane with respect to the beam transversal plane can influence the straightness measurement of a beam.

A. Distortions Simulation

Particular attention is paid towards these four cases of beam distortion:

1. Bending along X-axis
2. Barrel along Y-axis
3. Composition of case 1 and 2
4. Torsion along X-axis

The beam is simplified considering only the surface lying on the XZ plane which is the one related to the thickness of the beam. The laser plane which detects the beam straightness along the X axis, is simplified as a plane perpendicular to the XZ plane of the beam and intersecting the beam in its central transversal section. The plane is visualised in Fig. 12 in grey.

A simulation is performed considering the case of a laser triangulation system which is positioned in a deviated way such as the laser plane does not result parallel to the XY plane but it is rotated around the Y-axis of a different rotation angles. A step rotation angle is defined as 0.1°C and 17 cases are performed considering deviation from 0°C (perfectly aligned to the transversal section of the beam) to 8°C (maximum rotation). In Fig. 12 it is visible in black the intersection line between the laser plane and the surface of the beam, at the different misalignment angles.

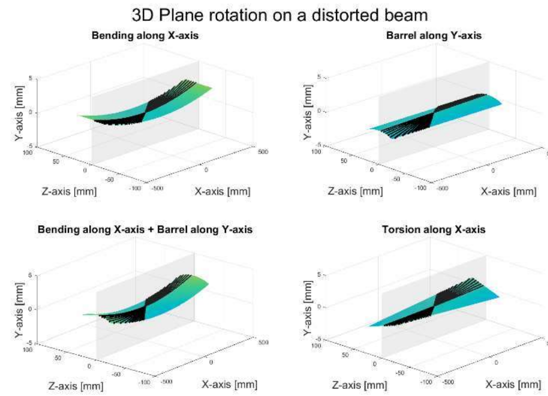

Fig. 12. Laser plane misalignment on a deformed beam

B. Straightness Deviation Calculation

The straightness deviation of the beam is defined, according to VDL Weweler bv. standards, as seen in Fig. 13. A straight line passing through the extremes of the bar is considered and the non-straightness is measured considering the maximum difference between the beam and this line. As outlined before, the requirement defined by VDL Weweler bv. for this application case is 1-2 mm. The measurement system therefore needs to have an accuracy of 0.1-0.2 mm to detect the beam straightness deviation.

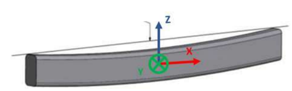

Fig. 13. Non-straight beam definition

Considering the simulation, the straightness value is calculated as the mean value of the Z-coordinates between the start and end point of the intersection line (in black in Fig. 12) while the misalignment value of the laser plane changes.

C. Discussion Of The Results

The laser plane misalignment is responsible of an erroneous straightness deviation estimation, which is different depending on the beam distortion case. In Fig. 14 it is presented in red the reference straightness deviation for the four cases, considering a perfect alignment of the triangulation system with respect to the beam: laser plane perpendicular to XZ plane and parallel to X-axis. Increasing the rotation angle of the laser plane (and therefore the misalignment), as to say considering an higher inaccuracy in positioning between the laser system and the beam, the straightness deviation (the blue line) differs from the reference one.

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Considering the case of the bending along X-axis the beam has a reference straightness deviation of about 1.8 mm (see Fig. 14) but increasing the misalignment angle the value of straightness is more and more underestimated, starting from 2° misalignment. In the case of barrel along Y-axis the reference straightness value is zero as the laser plane is parallel to the deformation. However, taking into account the misalignment angle of the laser plane the value of straightness is overestimated reaching 0.6 mm from 3° misalignment on. The third case considered represents a combination of the previous two and is the most critical as the value of straightness is always underestimated so no misalignment of the plane is acceptable. The last case is the one of torsion along Z-axis. In this case the straightness value is overestimated increasing the misalignment angle reaching a peak at 2-3° of misalignment.

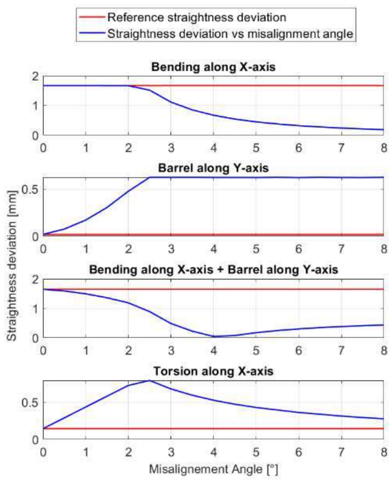

Fig. 14 Simulation of straightness deviation

D. Other sources of erroneous measurement estimation

The laser plane misalignment is clearly not the only factor to be considered when thinking about possible sources of errors in this measurement application use case. Other factors which might have a non-negligible influence on erroneous straightness deviation estimation of the steel bars might be:

- environmental effects such as temperature and dust;
- vibrations of the measurement system and the bar;
- laser line beam divergence;
- deformation of the bar due to temperature distribution;
- bar constraints and robot repeatability when positioning the component.

VI. Conclusion and Next Steps

This paper has presented a laser triangulation system to be used for straightness measurement of bars in metal industry in compliance to the Industry 4.0 paradigms. The use case is clearly representative of the ZDM strategy as it allows quality control in an industrial environment. As the target object to be analysed requires a high field of view of 1200 mm a proper design of the system is needed. The parametric study on the value of the Z-resolution proves how the choice of the main parameters is a compromise between system performance and feasibility. It is shown that the following parameters, in order, have the main influence on the Z-resolution value:

- camera sensor: a larger number of pixels means better resolution value but implies also higher costs and computational time;
- triangulation angle: larger angle means smaller Z-resolution values but implies larger overall dimensions of the system;
- X-FOV and Laser Stand-off distance: they are strongly dependent on the size of the object of interest and affect less the Z-resolution value.

The case study presented reaches a Z-resolution of 0.8 mm which can be pushed down to 0.01 using subpixeling. The simulation of the laser plane misalignment on the beam shows how this factor can influence the measured straightness considering different beam distortions. As it is shown the most critical case is the one with both bending and barrel distortion where every misalignment angle introduces an underestimation of the straightness deviation value. The misalignment angle is not the only one factor to be taken into account when measuring the straightness of a beam, therefore other simulations and tests should be done in order to optimize the process and increase the performances of the measurement system.

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References

[1] Deming, W.E. (1982) Quality, Productivity and Competitive Position. MIT Press, Cambridge

[2] Daryl Powell, Maria Chiara Magnanini, Marcello Colledani, Odd Myklebust, “Advancing zero defect manufacturing: A state of the art perspective and future research directions”, Computers in Industry, 136 (2022) 103596

[3] Hannah Ritchie, Max Roser and Pablo Rosado (2020) "CO_2 and Greenhouse Gas Emissions". Published online at OurWorldInData.org. Available: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions [Online]

[4] Naeem Khawar, Ullah Misbah, Tariq Adnan , Maqsood Shahid, Akhtar Rehman, Nawaz Rashid, and Hussain Iftikhar, “Optimization of Steel Bar Manufacturing Process Using Six Sigma”, Chinese journal of mechanical engineering, Vol. 29, No. 2, 2016

[5] About OpenZDM. Available: https://www.openzdm.eu/about/ [Online]

[6] Elisa Minnetti, Paolo Chiariotti, Nicola Paone, Gisela Garcia, Helder Vicente, Luca Violini, Paolo Castellini, “A Smartphone Integrated Hand-Held Gap and Flush Measurement System for in Line Quality Control of Car Body Assembly”, Sensors, June 2020

[7] Pilots of the OpenZDM project. Available: https://www.openzdm.eu/pilots/vdlwew/ [Online]

[8] What is Laser Triangulation? Available: https://www.movimed.com/knowledgebase/what-is-laser-triangulation/ [Online]

[9] Paolo Castellini, Andrea Bruni, Nicola Paone, "Design of an optical scanner for real time on-line measurement of wood-panel profiles," Proc. SPIE 6616, Optical Measurement Systems for Industrial Inspection V, 66164E (18 June 2007)

[10] Fisher, R.B.; Naidu, D.K. “A Comparison of Algorithms for Subpixel Peak Detection”. In Image Technology; Sanz, J.L.C., Ed.; Springer: Berlin/Heidelberg, Germsny, 1996; pp. 385–404

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